JET PROPULSION

Journal of the
AMERICAN ROCKET SOCIETY

Rocketry . . . . Jet Propulsion Sciences . . . . Astronautics

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ARS FALL MEETING—EL PASO-WSPG | SEPTEMBER 22-24 | SEE PAGE 265

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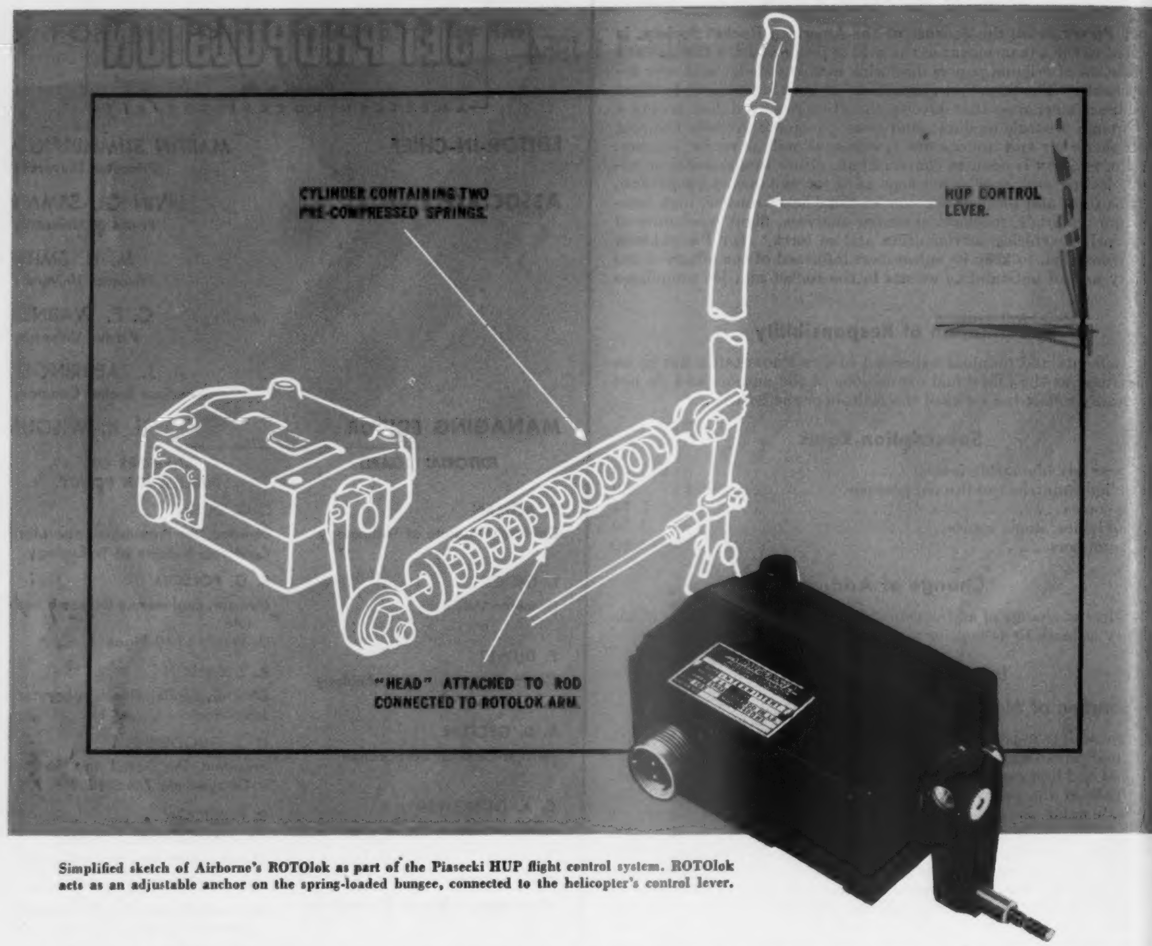

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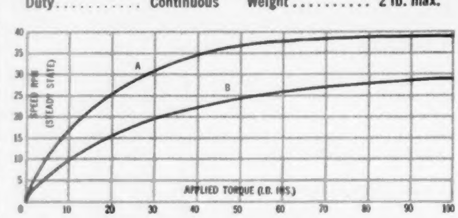

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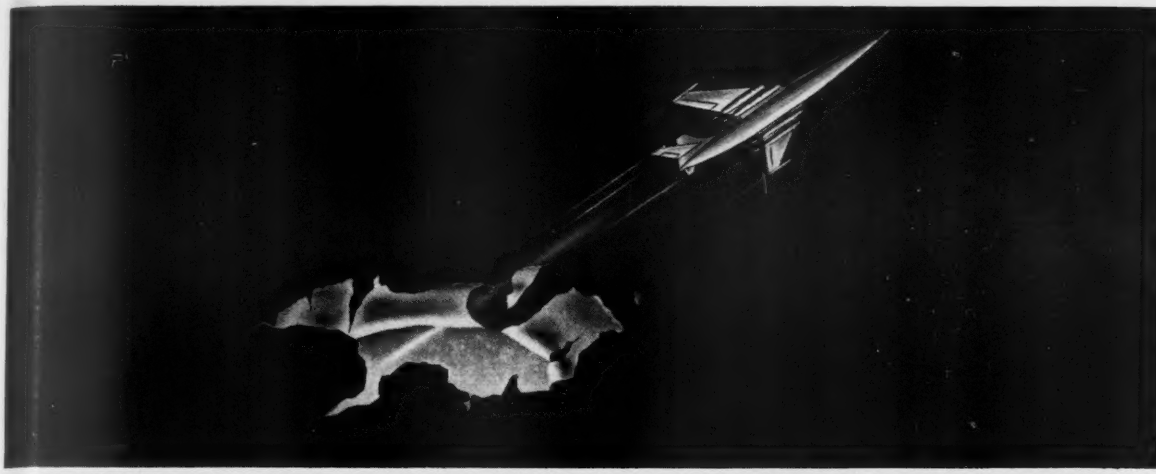

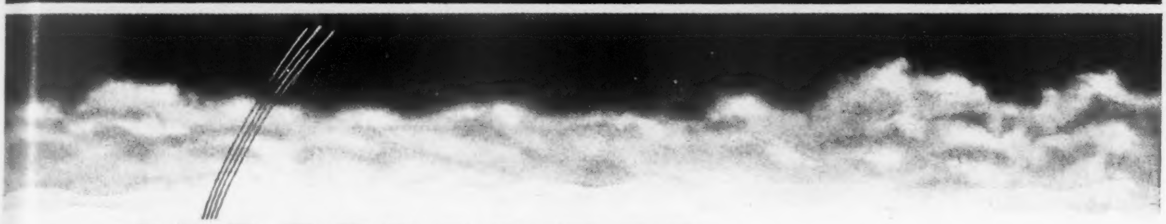

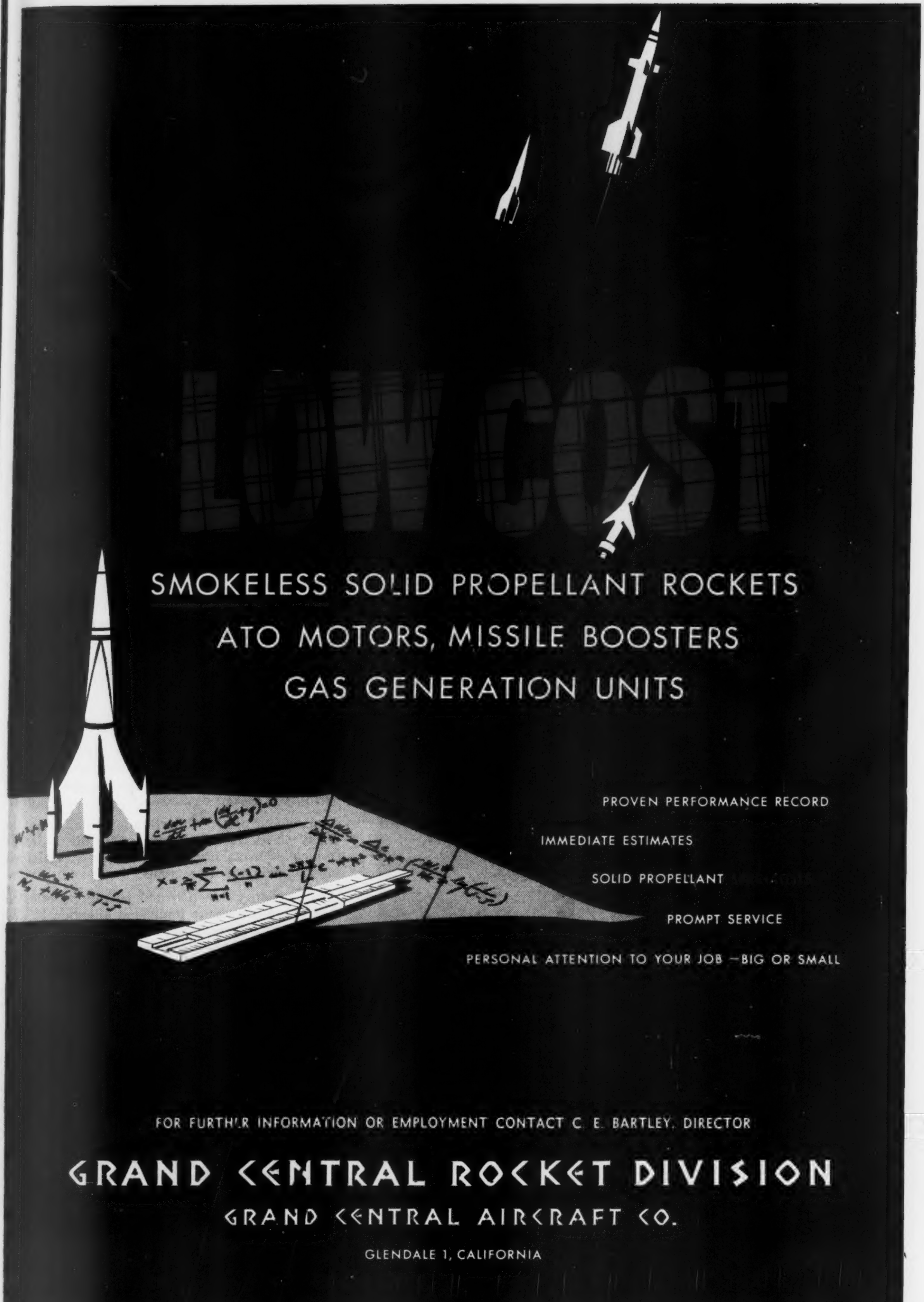
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Editor-in-Chief

MARTIN SUMMERFIELD

The Toxicity and Health Hazards of Rocket Propellants

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Rockets and other guided missiles require fuels which deliver extremely large amounts of energy to small combustion chambers in short periods of time. This requires combustible materials of high energy and reactivity coupled with powerful oxidizers. In many instances these fuels and oxidizers and their decomposition products are poisonous, and conditions attending their use may present hazards to personnel. Thus it becomes important for persons concerned with these materials to be educated in the nature of the hazards, how to prevent injury, and how to administer first aid if exposure occurs. The following report was prepared by a member of the research staff of the Army Chemical Corps Medical Laboratories, which conduct toxicological investigations in this field for the Armed Forces. It deals with the following propellants: (a) Fuels: ammonia, aniline, alcohols (ethyl, furfuryl, methyl), hydrazine, and JP-4. (b) Oxidizers: hydrogen peroxide, liquid oxygen, and red fuming nitric acid.

Introduction

TOXICITY may be defined as the inherent ability of a chemical to produce injury once it gains access to the body. Hazard may be defined as the likelihood of toxic injury prevailing during the handling and use of the chemical. From these definitions it may be seen that a chemical is not necessarily hazardous despite great toxicity because under the usual circumstances of handling the chemical the likelihood of toxic exposure may not arise. Also, a chemical of low or moderate toxicity may be extremely hazardous if the circumstances of its handling provides adequate opportunity for toxic injury.

Fundamentally, the best means of dealing with a poison is to avoid it. Often this is not possible, of course, and other means must be sought. Nevertheless, avoidance is, in fact, the basis for what is known as a program of "preventive medicine" applied by officials responsible for the safety of personnel who handle poisonous materials in some way. Avoidance or prevention of poisoning may take many forms or be achieved in one or more ways: use of protective clothing and equipment; adequate ventilation of facilities; safety-minded design of all equipment associated with the use, handling, and storage of toxics with the view of reducing the likelihood of toxic exposure. Hence, a concerted effort to reduce or eliminate hazard by supervisors, safety officers, engineers, operators, and others is required to devise and maintain safe handling procedures and other protective measures. An essential part of such a program is the education of all potential handlers in the hazard and its control, in self aid and first aid. Truly, the "ounce of prevention" being "worth a pound of cure" is an understatement. The link in a chain of safety precautions which fails is of no comfort to the victim of poisoning; hence all links must be sound. The nature and extent of preventive procedures are determined by the likelihood of exposure under the conditions of handling and use, by the potency of the poison, by the nature of its poisonous effect, and by the manner in which it gains access to the body (that is, skin contact, inhalation, etc.).

In the event of failure of the precautions at any point, removal of the poison from personnel or from equipment is the next step; actually, removal of personnel from contaminated spaces may be indicated. This implies advance provision for decontamination procedures and equipment effective for the particular poison, such as eyewashes and neutralizers. However, almost without exception, adequate water supplies for showers, eye baths, and sprinkler sprays at storage and using sites must be provided. In some instances provisions for whole body immersion in water may be highly desirable as well. Filters or canisters in respiratory protective devices should be changed often, preferably after each operation, to prevent accumulation of hypergolic mixtures. In general, consumption of alcoholic beverages by these exposed to toxic chemicals should be discouraged, and steady users of alcohol should be given other employment. Smoking should be discouraged while handling toxic materials, since this offers an insidious means for ingestion or inhalation of the toxic material from a cigarette or pipe contaminated with the hands.

Modern rocketry and guided missiles in general require fueling systems capable of delivering large amounts of energy to a small location, in variable but short periods of time. This means combustibles of high energy and reactivity coupled with powerful oxidizers. In many instances the fuels and oxidizers, and their decomposition products, may be toxic and the conditions attending their use may be hazardous. Thus, it behooves all concerned to become thoroughly acquainted with the nature and extent of the hazard, how to avoid it, and what to do in the event of accidental exposure of personnel. The following discussion is intended to present a sketch of the toxicity of several fuels and oxidizers in common use today, with suggestions on prevention of toxic exposures and on treatment of poisoning.

I Fuels

Ammonia (1, 2, 3)[2]

Ammonia used as a component of propellant mixtures is a concentrated solution of ammonia in water, producing a strong alkali. Its fumes are extremely irritating to the respiratory tract and to the eye. The inhalation hazard of am-

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[1] Coordinator of Military Chemicals Program, Physiology Division.

[2] Numbers in parentheses refer to References on page 236.

monia is low by virtue of the irritant effects of ammonia fumes so that voluntary exposure to amounts which would produce injury is quite unlikely.

The principal hazard from ammonia is in the contact of liquid with the skin and eye. Such contact may result in serious alkali burns unless promptly and vigorously acted upon—prompt and vigorous flushing with large amounts of water should generally suffice for the prevention of any serious injury. Handlers of ammonia who run the risk of liquid splash should be equipped with protective eyeglasses, suitable rubber gloves, aprons, and boots. Provisions for drenching showers should be made at all handling sites. After treatment with water, exposed parts of the body may be given a supplementary treatment of sponging with diluted (5 per cent) acetic acid (or vinegar) solution. This may be particularly desirable when there has been any appreciable delay in the application of water to an exposed site inasmuch as ammonia, being a strong base, may produce deep penetrating burns by virtue of soluble alkali metaprotein formation.

Aniline (2, 4, 5, 6)

Aniline is an oily liquid, normally colorless, but which darkens on exposure to light and air; it is flammable and has a burning taste and characteristic mild aromatic odor. It is a weak base forming salts with mineral and other acids and is miscible with organic solvents but only sparingly so with water. Its vapor density is about 3, its boiling point about 185° C, and its vapor pressure about 15 mm of mercury at approximately 80° C. Vapors of aniline do not present a toxic hazard by inhalation at ordinary temperatures because of the low volatility of aniline. However, at higher temperatures hazard may develop so that it is necessary to have respiratory protection. The maximum allowable concentration (MAC) of aniline vapors is fixed at 5 parts per million of air for an 8-hour daily exposure. It is a skin irritant. Although irritation and ulceration of the urinary bladder have been reported in the chronically exposed, it is no longer believed that bladder tumors are caused by aniline (8).

The principal toxic hazard from aniline is by way of the skin as the portal of entry to the body. Symptoms of poisoning by aniline may be conveniently separated into two classes: (a) Its effect upon the central nervous system gives rise to headache, weakness, difficulty in breathing or dyspnea, convulsions, and psychic disturbances. (b) The action of aniline upon hemoglobin of the blood gives rise to methemoglobin formation resulting in characteristic cyanosis or blueness of the fingernail beds, lips, and mucous membranes. It is claimed by some that methemoglobin formation by aniline is enhanced by ingestion of alcohol. Chronic exposures to aniline may give rise to eruptions upon the skin. The diagnosis of aniline poisoning is usually based upon a history of exposure and upon the characteristic intense blueness or cyanosis which occurs. Recently, it has been discovered that urinary excretion of a substance which combines with the "sulfonamide reagents" may be detected in exposed personnel sometime prior to the appearance of cyanosis or methemoglobin in the blood (6a). Periodic examination of the urine of aniline workers may well turn out to be a very useful index of the extent of exposure. Methemoglobin levels in the blood of 15 per cent or higher of the total hemoglobin is readily detectable by cyanosis and it is frequently accompanied by albumin and aminophenol in the urine. Lethargy and dyspnea occur at levels of 30 to 40 per cent methemoglobin, and 60 to 70 per cent methemoglobinemia generally is accompanied by a semistuporous condition of the victim. A simple test of suspected methemoglobinemia is as follows: venous blood shaken in air in the test tube becomes a cherry red in the absence of methemoglobin; in contrast, it maintains its dark bluish-purple hue in the presence of appreciable amounts of methemoglobin. This is a presumptive test and should always be subsequently confirmed by spectroscopic and other examination of the blood.

For those handling aniline, goggles, gloves, aprons, and rubber boots should be provided. Adequate respirators should be provided whenever there is reason to believe that high vapor concentration may prevail at a given operation. Since aniline is quite flammable, fireproof clothing should be provided. Clothing saturated with aniline should be removed immediately and suitably laundered, including the use of a dilute acetic-acid solution. Skin contaminated with aniline should be promptly washed with copious amounts of water followed by sponging with 5 per cent solution of acetic acid (or vinegar). Contamination of the eye should likewise be treated by washing with large amounts of water. The need for removal of contaminated clothing and adequate laundering cannot be overemphasized inasmuch as in addition to being a skin irritant, aniline is absorbed through the skin, as indicated earlier, and improperly laundered clothing may serve as a source of chronic poisoning.

Medical measures for the treatment of severe aniline intoxication should include intravenously administered methylene blue to reduce the methemoglobinemia. Facilities for administration of 100 per cent oxygen inhalation should be provided; in severe poisoning this may be life-saving.

Alcohols

Ethyl alcohol (2, 7, 8). Ethyl alcohol (ethanol, grain alcohol, alcohol) is a colorless flammable volatile liquid having a sweet, ethereal odor and a burning taste in its undiluted form. It is freely miscible with water and many organic solvents. Absolute (100 per cent) alcohol has a boiling point of 78.4° C, a vapor pressure of 40 mm of mercury at 25° C, and a vapor density of 1.59. It forms explosive mixtures with air within the following limits: upper 19 per cent and lower 3.28 per cent. 95 per cent ethyl alcohol, the most widely used grade, is somewhat different in its physical constants than the 100 per cent concentration; however, the differences are not great.

Although ethyl alcohol is toxic by inhalation, 1000 parts per million of air are considered safe for an 8-hour daily exposure, although irritation of the eyes and of the upper respiratory tract are often seen at this concentration; this concentration is not readily reached in open spaces. The principal toxic hazard is encountered by ingestion. The ingestion of 300 to 400 cc of ethyl alcohol within one hour by a nonhabituated drinker may result fatally. Denaturing agents often are the principal causes of severe intoxication with what is otherwise labeled alcohol and imbibed as potable ethyl alcohol.

Personnel protective measures consists of providing adequate ventilation wherever ethyl alcohol is to be used in enclosed spaces, and the removal of grossly contaminated clothing. If intoxicating amounts of alcohol have been ingested or inhaled, simple removal of the subject from the atmosphere and prevention of further ingestion may suffice to insure recovery. In the event that the subject is stuporous or comatose, medical assistance should be sought. Medical treatment should be directed to the maintenance of adequate hydration of the subject by the administration of suitable parenteral fluids and the administration of central nervous system stimulants as required such as amphetamine, caffeine, and picrotoxin.

Furfuryl alcohol (9). Furfuryl alcohol is a yellowish liquid, turning brown or dark red on exposure to light and air. It explodes violently with mineral acids and with some strong organic acids. It is freely miscible with water in all proportions and with most organic solvents. Its vapor density is slightly greater than three and its vapor pressure is 2 mm of mercury at 30° C. The inherent toxicity of furfuryl alcohol is not very great and its inhalation hazard is quite small owing to its low vapor pressure.

Skin absorption is slight and there is very little effect on skin and eyes. However, it is hazardous by virtue of the fact

that it may be ingested. In large amounts it has the usual effects of the alcohols upon the central nervous system. No special precautions for handling and use need to be observed except that individuals must be cautioned against ingestion. Contamination of the skin and eye may be adequately treated by flushing with adequate amounts of water. Contaminated clothing should be removed and washed to remove a source of skin irritation.

Medical treatment for the severely poisoned revolves around supportive measures for central nervous system depression which is common to the treatment of all alcohol poisoning, and around combatting dehydration and acidosis.

Methyl alcohol (2, 7, 8). Methyl alcohol (wood alcohol, methanol) is a colorless, flammable liquid which is volatile and has an odor very similar to that of ethyl or grain alcohol. Like ethyl alcohol, it is freely miscible with water and many organic liquids. Like ethyl alcohol, it is a very widely used solvent for many substances in many processes. In the pure state, methyl alcohol has a boiling point of 64.5° C, a vapor pressure of 96 mm mercury at 20° C, and forms explosive mixtures at the following concentrations: upper 36.5 per cent and lower 6.7 per cent. Methyl alcohol vapors have a density of 1.11.

Methyl alcohol may be toxic by ingestion, by skin absorption, and by inhalation. It is perhaps responsible for the great majority of cases of severe poisoning by ethyl alcohol to which it has been added as a denaturant. Exposure to vapors may produce the same train of symptoms as those due to ethyl alcohol inhalation, namely, signs commonly considered to be those of inebriation. In addition, nausea, vomiting, headache, and irritation of the respiratory tract may be seen. The vapor concentration of 200 parts per million of air are generally believed to be safe for 8-hour daily exposures. Larger amounts produce dizziness, ataxia, severe abdominal pain, convulsions, blindness, brain edema, and death. Blindness has followed ingestion of as little as 10 cc, although susceptibility varies greatly. It is believed that doses of 100–250 cc or less may result in death if taken by ingestion. Smaller doses often repeated may accumulate and may result in irreversible injury over a period of time. For this reason, periodic surveys of the atmospheric contamination at plant sites should be carried out.

Personnel protective measures should include adequate skin protection against contact, as well as adequate ventilation of all enclosed spaces. All personnel coming in contact with it, or likely to come in contact with it, should be thoroughly informed concerning the hazards of methyl alcohol.

Cases of exposure should be immediately removed from the atmosphere containing the alcohol, or if the accident has been by skin contact, clothing should be removed and the skin washed with copious amounts of water. If by ingestion, the subject should be made to vomit; this may be life-saving if ingestion has been recent. In addition, gastric lavage should be carried out. As with ethyl alcohol, measures should be instituted to prevent severe dehydration and circulatory collapse; coma should be treated as in ethyl alcohol poisoning.

Hydrazine (10, 11, 12)

Hydrazine is a colorless liquid with characteristic though not intense ammoniacal odor. Its fumes and vapors react violently with acids and flame and with other oxidizing agents. Hydrazine mixes with water and alcohols in all proportions. Its vapor pressure is about 18 mm of mercury at 30° C, and its boiling point is about 113.5° C. Its low vapor pressure is deceptive in that its vapors present a definite explosion hazard. Hydrazine presents a toxic hazard by inhalation, by skin contact, and by ingestion. In concentrations of 2000 parts per million or less, hydrazine vapors are quite toxic. However, at such concentrations, the vapors are quite irritating and this fact serves to limit acute exposures to high concentrations. Lower concentrations may produce irritation of the respiratory tract, and irritation and edema of the eyes. These effects do not necessarily provide adequate warning since they may not develop for some hours after exposure. Severe irritation of the eyes and even temporary blindness is possible after prolonged exposure. Effects of prolonged exposure usually include actions in the respiratory tract and upon the liver and very likely the kidney. The highest concentrations producing little or no injury to animals exposed over long periods of time are in the neighborhood of 5 parts per million.

Skin contact may result both in typical alkali burns which may be quite severe and in systemic intoxication. The latter is principally characterized by extensive fatty infiltration of the liver, kidney damage, and sometimes anemia. Protective clothing and equipment should consist of goggles, gloves, and fire-resistant protective clothing, and boots. It should be noted that rags saturated with hydrazine may inflame spontaneously if left lying around. Drenching showers for extensive skin exposure should be provided. In addition to water, 5 per cent acetic-acid solution baths or vinegar should be provided for soaking of exposed skin parts. The eye should be washed liberally with water.

Medical treatment for hydrazine burns follows that for burns of other origin. Treatment of liver injury should inlude a diet rich in protein, carbohydrate, and vitamins, and kidney injury should be treated as renal failure of similar extent and nature from other causes, as indicated by kidney tests.

JP-4 Fuel

JP-4 fuel is a jet engine fuel composed principally of aliphatic hydrocarbons and less than 25 per cent aromatic hydrocarbons. In odor and in appearance it very closely resembles such materials as kerosene and is a flammable volatile liquid distilling between 80 and 250° C.

JP-4 fuel is generally harmless when applied to the skin if it is promptly removed. However, if it is allowed to remain in contact with the skin for a long time, erythema and vesicles may develop on the skin. If the exposures are repeated and prolonged, the skin may be necrotized. The most frequently seen effects upon the skin are those of the drying by solvent action on the natural oils of the skin. There is little danger of systemic toxicity by skin penetration. However, if lead compounds are present in the fuel, lead intoxication may result by skin penetration. Vapor inhalation of 1000 parts per million or more produces symptoms closely resembling those of ethyl alcohol, although the symptoms are usually much more severe. Headache, nausea, vomiting, convulsions, prostration, cyanosis, coma, and even death have been reported. Chronic exposure is said to produce a form of intoxication with very vague symptomatology. Injury to the lungs has been observed when the fuel has been siphoned and portions aspirated accidentally. The symptoms after ingestion resemble those after inhalation except that they may be delayed in onset.

Personnel protective measures should include suitable skin covering, adequate ventilation of closed spaces, and respiratory protective devices such as those needed for gasoline. Removal of personnel to the open air after exposure should be carried out, and contaminated clothing after spillage should be promptly removed. The treatment for severe poisoning should be similar to that resulting from ethyl alcohol poisoning.

II Oxidizers

Hydrogen peroxide (13, 14)

Hydrogen peroxide (90 per cent) is a colorless liquid which decomposes spontaneously with the evolution of oxygen. Decomposition is accelerated by shaking, by impurities, or by

contact with large surfaces. It is a powerful oxidizing agent which combines explosively with combustible materials. It is miscible with water in all proportions.

Contact with the skin causes blanching of the area with a burning sensation. The skin effects disappear rapidly if the contact is very brief; however, severe burns may result from prolonged contact. Skin penetration is not a source of systemic poisoning. The inhalation of vapors produces redness and burning of the eyes and irritation of the nose and throat. Lacrimation, running nose, and excessive throat secretions result. Tissue damage by the vapors is not ordinarily encountered except after prolonged or repeated exposures; however, if hydrogen peroxide is present in the form of a fine mist or aerosol, tissue damage can result in the eye, trachea, and in the lungs. In experimental animals, a particularly insidious eye effect has been observed, namely, opacities of the cornea which appear several weeks after exposure. Hence, there should be periodic, frequent eye and upper respiratory examinations by the plant physician.

Personnel handling 90 per cent hydrogen peroxide should be provided with goggles or face masks and suitable skin protection in the form of gloves, aprons, and other clothing. Clothing of combustible materials such as wool and cotton should not be worn inasmuch as these materials may ignite spontaneously on contact with 90 per cent hydrogen peroxide; hence, safety clothing should be provided which should be made of polyvinyl chloride, polyethylene, or neoprene. Where there is a possibility of exposure to aerosol or fine mist, respirators and eye protection should be provided. In the event of gross contamination, safety showers should be used immediately. The eye should be promptly washed with large amounts of water. Serious skin injury should be treated as any burns of similar extent.

Liquid oxygen (15)

Liquid oxygen is a heavy, odorless and very slightly bluish liquid with a boiling point of −183° C at atmospheric pressure. It is explosive in contact with easily oxidizable materials; sometimes explosive mixtures are formed by combination of liquid oxygen with organic materials, which may be detonated by slight shock. Liquid oxygen as such is not toxic and is not irritating. Its hazard arises from its active support of combustion and its temperature. It should be stored in such a manner that it does not come in contact with flames or flammable materials, and where adequate ventilation can be provided. Accumulation of highly concentrated oxygen pockets should be avoided because cotton, wool, or other similar materials stored in such atmospheres may burn very violently upon ignition. Accidental spillage should be minimized to avoid injury by the coldness of the liquid, which can produce serious burns on contact with the skin or other portions of the body. Eyeglasses and gloves and other suitable skin protective equipment should be used by personnel handling liquid oxygen. Contaminated portions of the body should be treated as any other burned area and temperature effects minimized by soaking exposed parts in water.

Red Fuming Nitric Acid (8, 16, 17)

Red fuming nitric acid is a clear liquid ranging in color from yellow to reddish brown, strongly fuming, and extremely corrosive. The liquid is generally 87 to 92 per cent nitric acid with varying amounts of water and oxides of nitrogen, which are mainly nitrogen tetroxide. The fumes are yellowish red due to the nitrogen oxides, and are suffocating and poisonous; the fumes also contain nitric-acid vapors. Red fuming nitric acid is a powerful oxidizer readily attacking most organic materials. It reacts explosively with many organic materials such as aniline, xylidine, and furfuryl alcohol. It is precisely this property which makes it desirable for propellant use.

Red fuming nitric acid produces yellow staining of the skin after very brief contact; however, if contact is for any period, it is apt to result in a very severe burn. However, red fuming nitric acid may also produce poisoning by inhalation of the fumes. Fumes may arise from the decomposition of the acid itself, and it is for this reason that white fuming nitric acid has hazards similar to red fuming nitric acid. Decomposition of the acid to produce the fumes may be favored by contact with metals, organic materials, and possibly by the interaction of the oxides among themselves and with oxygen. Toxicologically, the most important nitrogen oxides are nitric oxide, nitrogen dioxide, and nitrogen tetroxide. Color or odor of the fumes cannot be relied upon primarily as a warning for toxic exposure. Of the three oxides, nitrogen dioxide and nitrogen tetroxide are probably the most important toxicologically, having severe effects upon the upper and lower respiratory tracts. In addition, they produce methemoglobin in the blood. Concentrations of 50 to 150 parts per million in the inspired air are said to be without discomfort; nonetheless, they may be extremely dangerous for even short periods. A safe concentration for 8-hour daily exposures should probably be 5 parts per million or less.

Shortly after an exposure, coughing, rapid asthmatic breathing, nausea, vomiting, and fatigue may be observed. There may be a large increase in the platelet count in venous blood, sometimes amounting to 60 per cent to 100 per cent. The blood pressure may fall and polycythemia may appear in the blood with resulting increase in hemoglobin content (no methemoglobinemia). The chest signs may become more severe with pain in the chest, spasmodic coughing, difficulty in breathing, these signs appearing several hours after the exposure. Fatal pulmonary edema and bronchopneumonia may appear. The variety in signs and symptoms is so great that all concerned with the handling of red fuming nitric acid and white fuming nitric acid should be alert to any unexplained symptomatology. Chronic exposure to oxides of nitrogen is said to produce wearing down and decay of the teeth, pulmonary emphysema, and irritation of the respiratory tract. Sometimes ulcerations of the nose or mouth are seen.

Personnel protective measures should begin at the preplacement medical examination. At this time the circulatory and respiratory system should receive special attention with the view to eliminating personnel who have bronchitis, asthma, or diseases of the heart. Frequent physical examinations should be carried out with special attention to the respiratory tract and the state of the teeth. Frequent surveys of the atmospheric contamination by oxides of nitrogen should be carried out. Adequate protective clothing such as gloves, aprons, and protection for the eyes should be provided. The only adequate protection against nitrous fumes in enclosed spaces is the so-called self-contained oxygen mask, inasmuch as the common gas-mask canisters do not provide adequate protection. It cannot be overemphasized that time is of the essence in skin, eye, or ingestion episodes, and that any delay may result in disaster. Drenching showers or immersion baths in the vicinity of any operation should be provided to deal with splash accidents. Where possible, bicarbonate of soda should be added to the baths for washing contaminated skin areas. Skin or eye contamination should be vigorously and promptly treated by flooding with large amounts of water. Washing should be carried out for at least 15 minutes. Contaminated clothing should be promptly removed and medical attention obtained without delay. Ingested nitric acid should be diluted by drinking water liberally. After the acid has been so diluted, vomiting may be encouraged; however, passing a stomach tube or vomiting may be a hazardous procedure in itself since the stomach may rupture if it has been severely burned. Hence, the decision for this should be left to the physician.

Casualties from inhalation of nitrous fumes should be placed in bed for 24 hours, even though the initial signs may not be alarming. Oxygen should be administered to combat the development of pulmonary edema as well as to fully oxy-

genate the blood. This should be done by nasal catheter if necessary until all danger from anoxia or pulmonary edema has passed. Artificial respiration should be administered cautiously in the event that the lung has been damaged. Respiratory depressants and cardiac stimulants should be avoided unless there are clear-cut signs of heart failure. Venesection for relief of pulmonary edema should be carried out with great caution if there are signs of impending circulatory collapse. Intercurring infectious complications such as pneumonia should be treated with antibiotics. Contamination of the eye should receive very prompt and vigorous attention inasmuch as seconds may count in the prevention of severe eye damage. Prompt washing with large amounts of water and with water containing 1 to 2 per cent sodium bicarbonate should be vigorously carried out until a physician arrives.

The Combustion Products of Fuels and Oxidizers

The hazard of combustion products of fuels and oxidizers which have been discussed in the past paragraphs may be summed up as follows:

(a) Little is known concerning the identity of the intermediary oxidation products of the rocket combustion of fuels and oxidizers mentioned in the foregoing paragraphs. However, the principal combustion products of toxicological interest in this discussion are believed to be carbon monoxide and the oxides of nitrogen, the latter wherever nitrogenous fuels and/or nitrogen containing oxidizers are used. Much is known concerning the toxicity of carbon monoxide; hence, it is not necessary to dwell in detail here upon the hazards of carbon monoxide. It should suffice here to indicate that adequate ventilation will provide necessary relief from exposures and will eliminate further hazard; artificial respiration with oxygen for the severely poisoned is necessary. When the halogens are an important part of the fuel system, hydrogen halides, viz., chlorides, must be considered in the picture of hazard. Similarly if sulfur is present, the oxidation products of sulfur, such as sulfur dioxide, sulfur trioxide, and sulfuric acid must likewise be considered. However, the fumes from the latter are generally so irritating as to preclude voluntary exposure of personnel to dangerous amounts.

(b) The ideal approach to the problem of combustion products is adequate, periodic, atmospheric surveys, not only of a quantitative nature for specific expected products but also of a qualitative nature in an attempt to determine unknown toxic contaminants in the air. This is particularly true where new fuels and oxidizers are being developed; this is to the end that hazard may be eliminated or that atmospheric contamination may be reduced to safe levels.

Discussion

Certain general remarks in the introduction were necessarily sketchy. These may now be extended to emphasize certain aspects of the problem of dealing with toxic materials.

The prevention of injury is of paramount importance in dealing with hazardous chemicals, just as it is in dealing with explosives, electricity, or disease. A prime requisite for a successful program of prevention is the proper training of all concerned in the inherent dangerous properties, including toxic potential—the subject of this report—and in the proper use of procedures and devices established beforehand which are intended to prevent injury. All concerned must be convinced that the dangers of the propellant chemicals described in the preceding passages are not exaggerated. At the same time, however, it should be stressed to all that these materials can be handled safely, just as explosives handlers and electrical workers, to cite two common examples, deal safely with no less hazardous situations daily. This emphasizes that handlers must respect but not fear that which they handle, and this in turn means that each supervisor must be thoroughly familiar with the psychological make-up of each member of his team in order to prevent (a) callousness and carelessness in the overconfident and incredulous, and (b) almost paralyzing fear, which in itself may make for accident proneness, in the overcautious or timid. A daily appraisal of the fitness of all team members is of great value.

Concerning general protective measures, it is axiomatic that suitable personal protective equipment, in addition to safety devices on materiel, be provided as indicated in connection with each chemical in the preceding pages. However, the versatility and effectiveness of water in maintaining safety in the presence of a very wide variety of toxic hazards are not generally stressed as much as they deserve. Its ubiquity and general usefulness for other purposes—hence, already procured and provided—adapt it admirably as an indispensable item among those in the first line of protection. Hence, it must be available for dispensing by failure-proof mechanisms, which need not be more complex than common hose lines, showers, tanks, or vats for whole body immersion, eye-wash basins, and other means, as local requirements dictate and local capabilities permit. Respiratory protective devices must obviously be tested frequently, since certain parts may lose effectiveness not apparent on inspection. Canisters, filters, and the like used against one chemical hazard should be discarded to render impossible use against another, so as to prevent opportunity for forming dangerous mixtures with the first. It is, in any case, of great importance that the presence of protective gear of any kind not foster relaxation of vigilance or encourage a false sense of security. An indispensable part of preventive efforts is what may be termed "good housekeeping," viz., scrupulous attention to prompt elimination of contaminated sites, however small, be they in the laboratory, plant, or storage shed. Together with good personal hygiene in prompt removal of hazardous materials from skin and clothes, good housekeeping can go far in preventing the insidious growth of toxic situations. Smoking should be discouraged where it offers a means for ingestion or inhalation of toxic materials.

In the event of failure of preventive efforts, i.e., an accident which exposes personnel, speed in application of first aid and self aid is critical in minimizing injury from these propellant materials. This fact cannot be overemphasized, and in general drenching of body parts exposed to liquid or removal of the subject from a fume- or vapor-contaminated atmosphere must be carried out without the slightest delay. This is especially important in connection with eye contamination with red fuming nitric acid, with urgency in treating skin exposure to liquid red fuming nitric acid being a close second. Literally, in this case, seconds count if injury is to be successfully averted or progression of injury prevented. Though chemical facts may argue for the use of a chemical antidote, the time available for any successful treatment of liquid splash injury by red fuming nitric acid is so short that failure to apply readily available water by seconds, while searching for sodium bicarbonate solution, may spell disaster. All concerned must be convinced that self-aid procedures exist which, when promptly and properly applied, are not less, but rather more effective, for all their simplicity, than elaborate measures applied too late. Like considerations apply no less forcibly to first aid, properly and promptly administered. As nearly concurrently as possible, medical attention should be sought.

When compelling circumstances require exposure in spite of known hazard, such as unprotected entry into a contaminated atmosphere, risks are taken when they are clearly outweighed by the known consequences of not taking the risks. Conversely, those concerned in dealing with new chemicals of suspected, though unknown, hazard should not expose themselves or others unjustifiably. In this connection, competent toxicological and medical advice should be sought.

(Continued on page 236)

Heat Transfer and Frictional Pressure Drop Characteristics of White Fuming Nitric Acid[1]

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An experimental investigation was conducted to determine the heat transfer and fluid friction characteristics of white fuming nitric acid (WFNA) under conditions simulating regenerative cooling of a rocket motor with WFNA. Under conditions where no local boiling occurred in the test section the recommended heat transfer equation (modified Colburn equation) is[4]

$$j = 0.023\ N_{Re}^{-0.2}$$

where all physical properties of the WFNA are evaluated at the bulk temperature of the WFNA. The recommended equation is similar to those found for pure liquids and is exactly the same as the equation correlating the heat transfer data of water obtained at high pressures and heat flux densities (7).[5] The Fanning friction coefficient with heat addition, f_q (when no local boiling occurs), is related to the isothermal friction coefficient, f_{iso}, by the standard relationship (13)

$$\frac{f_{iso}}{f_q} = \left(\frac{\mu_{bulk}}{\mu_{surface}}\right)^{0.12}$$

where μ_{bulk} and $\mu_{surface}$ are the WFNA viscosities evaluated at the bulk and surface temperatures, respectively. The isothermal friction coefficients in the above relation were determined experimentally and were found to be the same as the coefficients determined by other investigators using pure liquids as the test fluid.

Nomenclature

A = test section flow area, sq ft
C_p = specific heat at constant pressure, B/lb F
D = diameter of test section, ft
f_{iso} = Fanning friction factor under isothermal conditions, $f = \Delta P g \gamma A^2 D/2G^2 L$, dimensionless
f_q = Fanning friction factor with heat addition, dimensionless
G = weight flow rate, lb/sec
g = acceleration due to gravity, ft/sec^2
h = film coefficient of heat transfer, B/sq ft hr F
j = Colburn j-modulus $= h/MC_p(N_{Pr})^{2/3}$, dimensionless
k = thermal conductivity, B/ft hr F
L = test section length, ft
M = weight flow per unit area, lb/sec sq ft
N_{Nu} = Nusselt number $= hD/k$, dimensionless
N_{Pr} = Prandtl number $C_p\mu/k$, dimensionless
N_{Re} = Reynold number $\rho DV/\mu = 4G/\pi g D\mu$, dimensionless
P = pressure, absolute, lb/sq in.
ΔP = pressure drop across the length of the test section, lb/sq in.
μ or μ_{bulk} = viscosity evaluated at the bulk temperature lb hr/sq ft *or* centipoise
$\mu_{surface}$ or μ_s = viscosity evaluated at the inside surface temperature of the test section, lb hr/sq ft *or* centipoise
γ = specific weight, lb/cu ft
ρ = density, g/cc or slug/cu ft

Introduction

In recent years a number of investigations have been conducted on forced convective heat transfer to liquids where large temperature gradients occurred at the heated surface. Most of the stimulation in this particular phase of heat transfer can be attributed to the increased activity in the field of rocket propulsion. Accordingly, since white fuming nitric acid (hereafter abbreviated WFNA) is one of the widely used oxidizers, a study of the convective heat-transfer char-

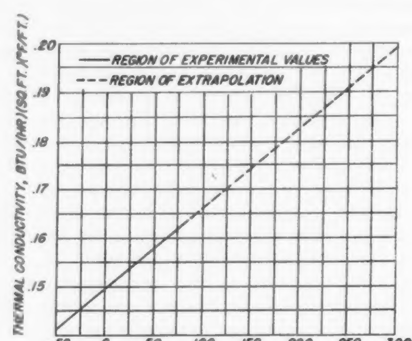

FIG. 1 RECOMMENDED VALUES OF THERMAL CONDUCTIVITY OF WHITE FUMING NITRIC ACID. COMPOSITION (BY WEIGHT) HNO_3, 99.01; NO_2, 0.46; H_2O, 0.53. (REFERENCE 4)

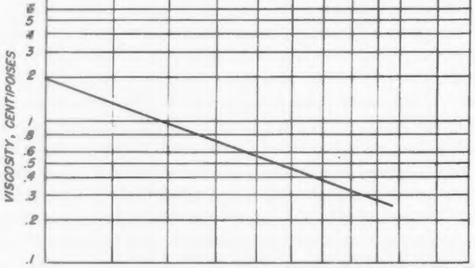

FIG. 2 RECOMMENDED VALUES OF VISCOSITY OF WHITE FUMING NITRIC ACID. COMPOSITION (BY WEIGHT) HNO_3, 97.35; NO_2, 1.57; H_2O, 1.08. (REFERENCE 4)

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[4] The symbols are defined in the Nomenclature.

[5] Numbers in parentheses refer to the References at end of paper.

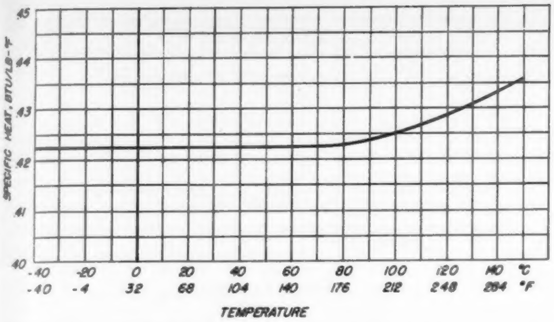

FIG. 3 RECOMMENDED VALUES OF SPECIFIC HEAT OF WHITE FUMING NITRIC ACID CONTAINING 95 TO 97.5 PER CENT (BY WEIGHT) HNO_3. (REFERENCE 4)

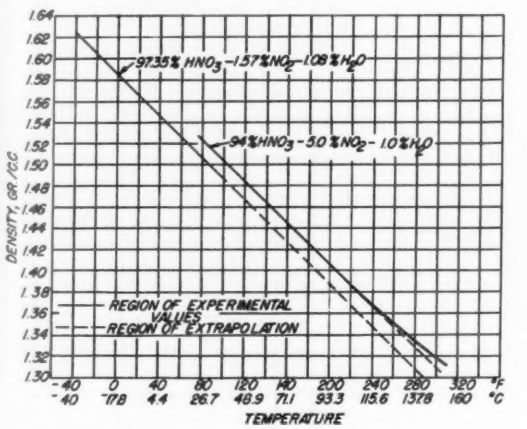

FIG. 4 RECOMMENDED VALUES OF DENSITY OF WHITE FUMING NITRIC ACID. (REFERENCE 4)

acteristics of WFNA has been conducted at the Purdue University Rocket Laboratory under the sponsorship of the National Advisory Committee for Aeronautics.

Information on the heat transfer and frictional pressure

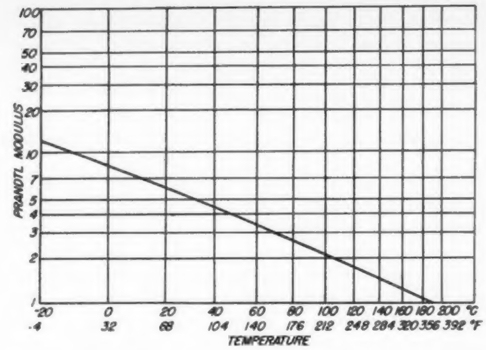

FIG. 5 RECOMMENDED VALUES OF PRANDTL MODULUS FOR WHITE FUMING NITRIC ACID. COMPOSITION (BY WEIGHT) HNO_3, 97.35; NO_2, 1.57; H_2O, 1.08. (REFERENCE 4)

drop characteristics of WFNA are required for the design of regeneratively cooled rocket motors utilizing that liquid as a coolant. The correlations of heat transfer measurements taken at low heat flux densities on pure liquids were not considered adequate for the above purpose for two reasons: (a) because of the high heat flux densities encountered in the operation of rocket motor (1, 2, 3), and (b) the possibility that the WFNA might decompose under the conditions of high wall temperatures resulting in a complex mixture of nitric acid, oxides of nitrogen, and water.

While the heat transfer apparatus was being designed and built, Professor W. L. Sibbitt and his associates at Purdue University determined the physical properties of WFNA over a range of temperatures under the same contract with NACA (4). Figs, 1, 2, 3, 4, and 5 present the recommended values of the physical properties—thermal conductivity k, viscosity μ, specific heat C_p, density ρ, and Prandtl's modulus N_{Pr}—as functions of WFNA temperature.

Apparatus and Instrumentation

Fig. 6 is a diagrammatic sketch of the flow circuit(5). The test section is a Haynes Stellite Alloy 25 tube having an OD of $^5/_8$ in., a wall thickness of 0.043 in., and a total length of 24 in. Temperatures of the outside wall of the test section were

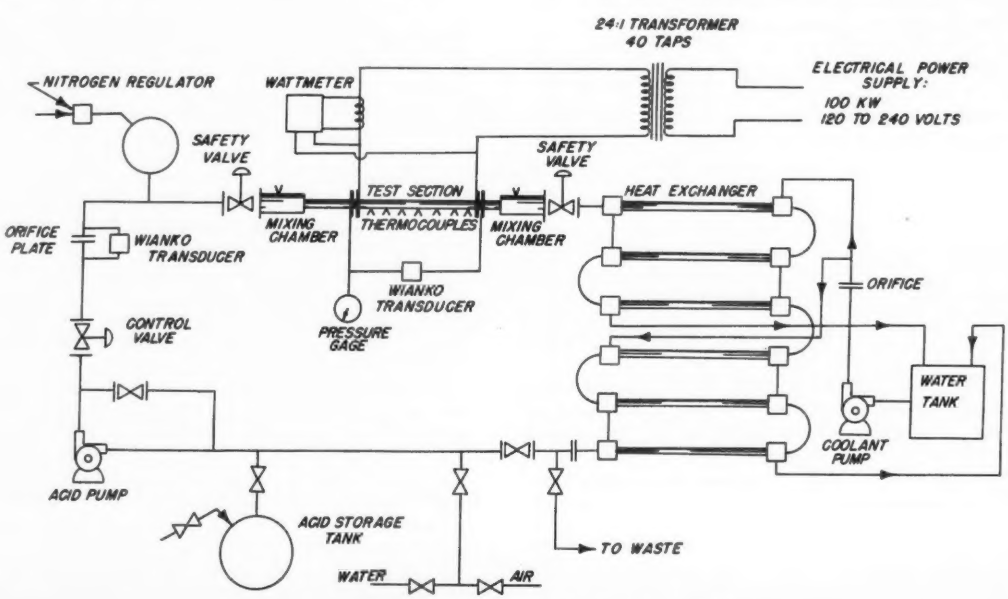

FIG. 6 DIAGRAMMATIC SKETCH OF THE TEST APPARATUS

measured at the 14 locations; two thermocouples at each station spaced at 3-in. intervals along the length of the tube. The test section was insulated thermally by a $^1/_2$-in. layer of Sauerisen cement and 12 in. of glass wool with two concentric aluminum-foil radiation shields spaced at radii of 2 and 6 in., approximately. One mixing chamber was installed upstream to the test section and the other downstream. They comprised three concentric tubes arranged so that the acid makes three passes longitudinally through the mixing chamber before its temperature is measured. To insure a fully developed isothermal boundary layer and uniform turbulent velocity profile for the WFNA entering the test section, a starting length of tube equal to approximately 25 tube diameters was inserted between the upstream mixing chamber and test section.

The test section was heated with a-c current and cooled by forced convection by flowing WFNA through it. A 240-volt a-c single-phase generator and multitap transformer having a maximum power rating of 100 kw furnished the electric power for heating the test section. The resistance of the test section, however, limited the maximum power for heating to 67 kw because of current limitations of the multitap transformer (2500 amp).

After calibrating the instruments, the performance of the complete apparatus and its operating characteristics were studied by measuring the convective heat-transfer coefficients for distilled water over the Reynolds number range from 50,000 to 166,000. The results obtained were in good agreement with those published in the literature.

In the experimental program the variable most difficult to measure with accuracy was the outside surface temperature of the test section. It was estimated that the maximum probable error in that measurement is −4 per cent. Due to the latter error and all other measurement errors, the uncertainty of the thermal conductivity of the test section material, and the uncertainty of the value of the density of WFNA, the values of heat transfer coefficient and the Fanning friction coefficient are believed to be accurate only to within ±7 per cent. However, when the heat transfer coefficient is combined with the available property data for WFNA in calculating the dimensionless j-modulus, the probable maximum uncertainty in the j-modulus is approximately 16 per cent, due to uncertainties in the physical property data of the WFNA. Even larger uncertainties are possible if the WFNA composition used in the apparatus varies significantly from that used in obtaining the data on physical properties.

Experimental Results

Heat transfer and friction pressure drop data were obtained for the range of variables listed in Table 1.

Table 1

1	Heat flux density	0.13 to 1.4 Btu/sq in. sec
2	Pressure	64 to 165 psia
3	WFNA inlet temperatures	50 to 137 F
4	Reynolds number	55,000 to 220,000

Fig. 7 presents the measured values of the temperature of the outer wall of the test section and the bulk temperature of the WFNA as functions of the length of the test section. With the figure a list is presented of other measurements which were made (the weight flow, heat flux density inlet pressure, and pressure drop across the length of the test section).

Convective Heat Transfer

The forced convection heat-transfer data for WFNA are summarized in Fig. 8. The latter presents the Colburn j-modulus[6] as a function of the Reynolds number. The heat transfer coefficient, h, in the relationship for j is based on the difference of the average of the inner wall temperatures of the test section, and the average bulk temperature for the WFNA. The physical properties of the WFNA used in calculating j and N_{Re} were evaluated at the average bulk temperature of the WFNA, and not at the film temperature as recommended by Colburn (13).

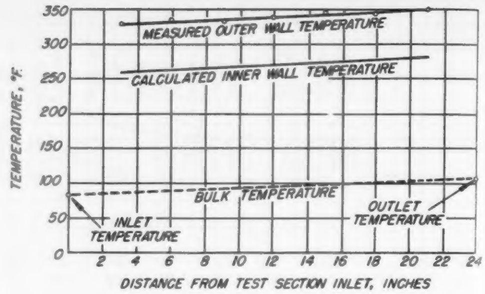

FIG. 7 TEMPERATURE DISTRIBUTIONS DURING A TYPICAL TEST. OTHER MEASUREMENTS FOR THE SAME TEST: WEIGHT RATE OF WFNA, 2.26 LB/SEC; HEAT FLUX DENSITY, 0.63 BTU/SQ IN. SEC; INLET PRESSURE, 66 PSIA; PRESSURE DROP ACROSS TEST SECTION, 1.35 PSIA

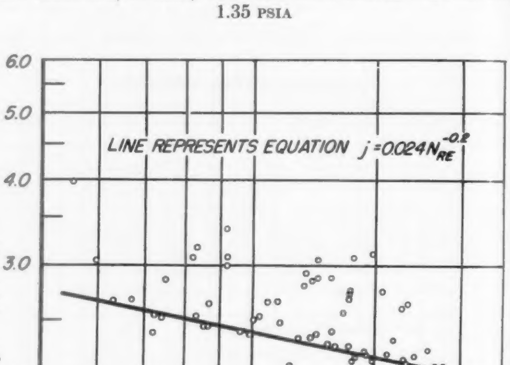

FIG. 8 CORRELATION OF HEAT TRANSFER DATA. CONDITIONS: TEST SECTION, 24 IN. LONG, 0.539 IN. I.D.; INLET PRESSURES, 64 TO 165 PSIA; INLET WFNA TEMPERATURES, 50 TO 137 F; HEAT FLUX DENSITIES, 0.13 TO 1.4 BTU/SQ IN. SEC. PHYSICAL PROPERTIES OF ACID DETERMINED AT THE AVERAGE BULK TEMPERATURE OF THE WFNA

Several of the points in Fig. 8 lying above the curve recommended by the authors for correlating the data were obtained when the inside surface temperature of the test section was above the saturation temperature of the WFNA (local boiling) and, therefore, were not expected to correlate. The points which lie considerably below the curve were obtained in Run 28 where the acid was recirculated through the apparatus for several hours. Fig. 9 presents the deviation of the results of Run 28 from the correlation curve as a function of the time that the acid has been recirculated through the

[6] See the Nomenclature at beginning of paper.

test apparatus. It is seen that the heat transfer coefficient decreased significantly with time; after the WFNA had been recirculated for 8 hours the coefficient decreased by 26 per cent. The reason for that decrease is not known definitely at this time. Scale, dissociation of the WFNA, and corrosion of the test section all occur, and which of these influences predominates still requires investigation.

Fig. 10 presents the j-modulus as a function of N_{Re} for all of the purely forced convective data. Included are the results obtained from Run 28, corrected to zero circulation time. The correlation equation is

$$j = 0.024\,(N_{Re})^{-0.2}\ldots\ldots\ldots\ldots\ldots\ldots[1]$$

where all physical properties of the WFNA are evaluated at the average bulk temperature. The maximum deviations of the j-modulus from the correlation curve is plus 32 and minus 9 per cent.

By increasing the coefficient of Equation [1] it would be possible to reduce the maximum deviation of any point to ±20. Such a change, however, places the majority of the points below the correlation curve. Consequently, Equation [1] is considered to be the most satisfactory correlation equation for these data. The points which lie farthest above the correlation curve in Fig. 10 represent the data taken in Runs 2, 24, and 29. These points are indicated by circles with dashes appended. Each of these afore-mentioned runs was made with a different test section and with a new charge of WFNA, and in each case was the first run (series of test points) in the respective test section. After Runs 2 and 29 the test section had to be replaced. The same test section was used, however, for Runs 24, 25, and 26, but with different charges of WFNA. The data obtained from Runs 25 and 26 correlated with the recommended curve. Several other runs made with new test sections and fresh WFNA gave heat transfer coefficients which correlated with the recommended correlation equation. The discrepancies shown by Runs 2, 24, and 29 are not completely resolved, but it is felt that they may be due to variations in the composition of the WFNA.

A correlation of the heat transfer results was also made employing an equation similar to that of Sieder and Tate(6). The result is

$$j = 0.022\,N_{Re}^{-0.2}(\mu/\mu_s)^{0.14}\ldots\ldots\ldots\ldots\ldots[2]$$

where μ and μ_s are the viscosities of the liquid at the bulk and inner surface temperatures, respectively. Equation [2] does not correlate the data more satisfactorily than does Equation [1].

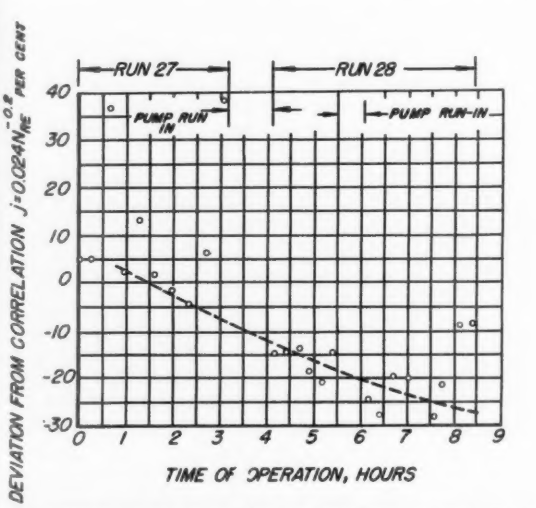

FIG. 9 EFFECT OF SCALE AND/OR DISSOCIATION ON THE HEAT TRANSFER CORRELATION. RUNS 27 AND 28. PHYSICAL PROPERTIES EVALUATED AT AVERAGE BULK TEMPERATURE OF THE WFNA

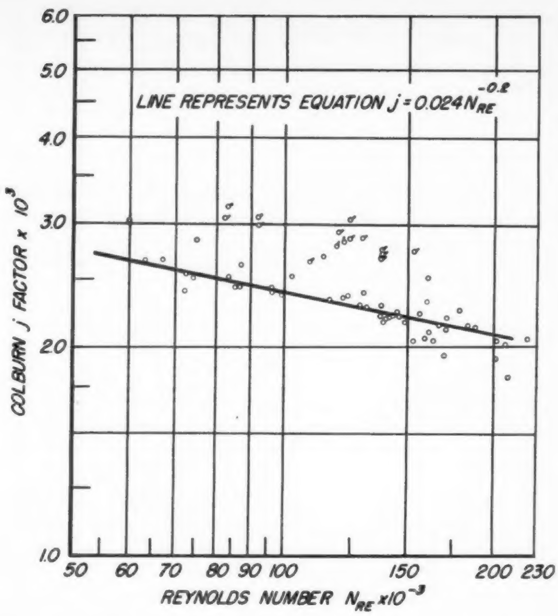

FIG. 10 CORRELATION OF HEAT TRANSFER DATA. SAME CONDITIONS AS FIG. 8, LOCAL BOILING POINTS NOT PLOTTED AND DATA ON RUN 28 CORRECTED TO ZERO CIRCULATION TIME

A study of the effect of test section length upon the heat transfer coefficient was made by calculating the local heat-transfer coefficients at various stations along the test section. These data when plotted are correlated by an equation of the form

$$j = CN_{Re}^{-0.2}\ldots\ldots\ldots\ldots\ldots\ldots\ldots[3]$$

where C is a constant and can be determined from Fig. 11.

Fig. 11 presents C as a function of L/D for WFNA and, for comparison, includes results obtained with water at high pressures and at high heat flux densities at UCLA (7) and M.I.T. (8). The results presented by M.I.T. were correlated by using the film temperature for evaluating the physical properties of the water, while those presented by UCLA on water and by Purdue on WFNA employed the bulk temperature of the liquid. Since the coefficient in Equation [3] decreases with the L/D ratio of the test section, it is recommended that Equation [1] be modified to read as follows

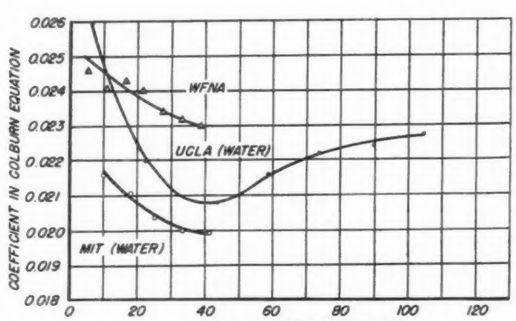

FIG. 11 EFFECT OF L/D RATIO ON HEAT TRANSFER CORRELATION. COEFFICIENT DETERMINED BY UCLA AND FOR WFNA USING PHYSICAL PROPERTIES DETERMINED AT THE BULK TEMPERATURE AND BY M.I.T. USING THE FILM TEMPERATURE. (REFERENCES 7 AND 8)

$$j = 0.023\, N_{Re}^{-0.2} \qquad [4]$$

Equation [4] is recommended for calculating the forced convective heat transfer coefficient, h, for WFNA. It has the advantage of simplicity and gives conservative values of h.

Friction Pressure Drop

Experiments were conducted to obtain the isothermal Fanning friction coefficient for WFNA for the range of Reynolds numbers investigated (see Table 1). The results obtained are presented in Fig. 12 and compared with those published by Moody (9).

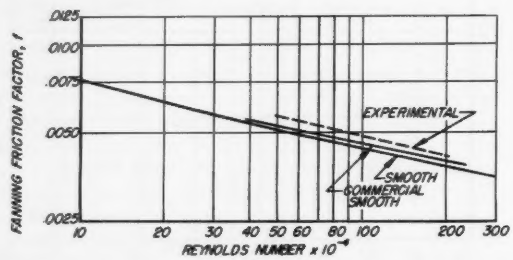

FIG. 12 ISOTHERMAL FANNING FRICTION FACTORS FOR SMOOTH TUBE. DATA FOR SMOOTH AND COMMERCIAL SMOOTH TUBE FROM REFERENCE 9. THE "EXPERIMENTAL" CURVE FOR WFNA WAS DETERMINED USING PHYSICAL PROPERTIES EVALUATED AT THE AVERAGE BULK TEMPERATURE

Within the convective heat-transfer region (without local boiling) it was found that the pressure drop with heat addition (and consequently the friction coefficient f_q) was consistently smaller than the isothermal pressure drop at the same Reynolds number. For a range of bulk temperatures investigated (60 to 145 F) it was possible to relate the isothermal friction coefficient to the friction coefficient with heat addition, both measured at the same Reynolds number, by the relation

$$\frac{f_{iso}}{f_q} = \left(\frac{\mu_{bulk}}{\mu_{surface}}\right)^{0.12} \qquad [5]$$

Fig. 13 compares the experimental values of the nonisothermal friction factor f_q with those calculated by means of Equation [5].

The experimental data on friction pressure drop were employed in the Reynolds analogy, as presented by Boelter,

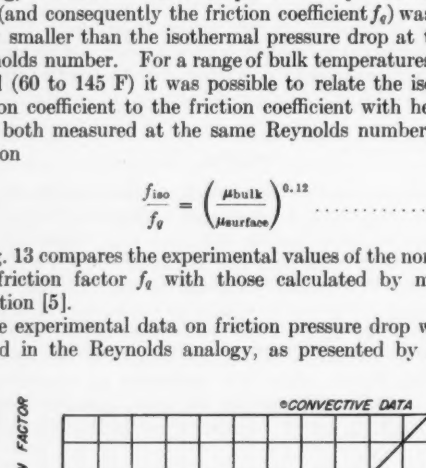

FIG. 13 COMPARISON BETWEEN CALCULATED AND EXPERIMENTAL NONISOTHERMAL FANNING FRICTION FACTORS. PHYSICAL PROPERTIES EVALUATED AT THE AVERAGE BULK TEMPERATURE OF THE WFNA

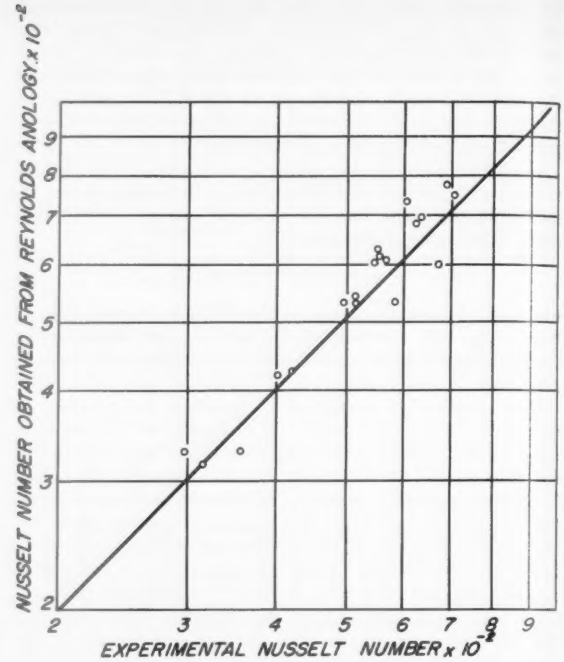

FIG. 14 RELATIONSHIP BETWEEN EXPERIMENTAL NUSSELT NUMBER AND THE NUSSELT NUMBER OBTAINED FROM REYNOLDS ANALOGY. (REFERENCE 10) PHYSICAL PROPERTIES EVALUATED AT THE AVERAGE BULK TEMPERATURE OF THE WFNA

Martinelli, and Jonassen (10), to predict the Nusselt number for the WFNA. The results are presented in Fig. 14 where the experimental values of the Nusselt number are plotted as a function of the Nusselt number calculated by the Reynolds analogy. These results are quite satisfactory, although it should be pointed out that the data from Runs 2, 24, and 29 are not included because those data are open to suspicion.

Local Boiling Heat Transfer

Some preliminary investigations were made in the local boiling region. Efforts to correlate the heat transfer coefficients for WFNA by methods utilized by other investigators using other liquids were not successful (7, 8, 11, 12). Plotting q/A as a function of "excess temperature," which is defined as the difference between the inner tube surface temperature and the saturation temperature of the acid, did not give any correlation, probably due to the uncertainty of the saturation pressure data, which was extrapolated from vapor pressure measurements taken below 20 psia. Fig. 15 presents the extrapolated values of vapor pressure.

Another method for presenting local boiling heat-transfer data is to plot the heat flux density against the temperature difference $t_{surf} - t_{bulk}$ for a constant weight flow rate. Fig. 16 is an attempt to correlate the WFNA heat transfer data on that basis. The curves obtained are geometrically similar to those obtained by other investigators with fluids other than WFNA. It is seen that for each weight flow rate the slope of the curve increases sharply as the surface temperature of the tube reaches the saturation temperature, indicating that large increases in the heat transfer rate are accompanied by only small increases in surface temperature. However, the results with pure liquids show that for a constant pressure the data in the boiling region all fall on one curve. The experiments with WFNA at the same pressure gave two curves in the boiling region, the curves being approximately 40 F apart. Again the lack of correlation may be due to variation in the saturation temperature with change in composition of the WFNA.

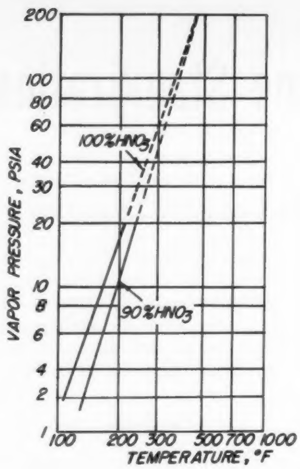

FIG. 15 EXTRAPOLATION OF VAPOR PRESSURE MEASUREMENTS (REFERENCE 4)

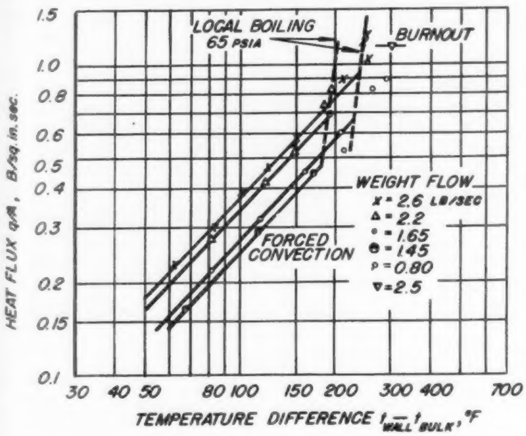

FIG. 16 FORCED CONVECTION WITH AND WITHOUT LOCAL BOILING BULK TEMPERATURE, 91 TO 122 F; PRESSURE 65 PSIA

Friction Pressure Drop with Local Boiling

As was noted previously, in the convective region, without local boiling, the pressure drop decreased as the heat transfer rate increased (surface temperature is increased) at constant flow conditions. However, as shown in Fig. 17, when the surface temperature reached the saturation temperature the pressure drop increased. No satisfactory analytical method was developed for predicting the friction coefficient in the local boiling heat transfer regime.

The phenomenon of local boiling is thought to increase the pressure drop because: (a) the vapor bubbles which are formed at the inside surface of the tube impose a drag force on the fluid flow; and (b) the formation of vapor at the surface of the tube causes the local value of the kinematic viscosity at the wall to increase, signifying that the viscous forces of the fluid are becoming more prominent at the wall.

It should be emphasized that the experiments in the local boiling region were more or less exploratory, and research is continuing at Purdue University on this phase of the heat transfer problem.

Conclusions

1 Over the range of conditions investigated (see Table 1) in the forced convection region (without local boiling), the heat transfer results can be satisfactorily correlated by Equation [4]. The latter equation was originally derived for high-pressure water. The pressure drop relations are similar to those found for pure liquids. The heat transfer and pressure drop data indicate that the effect of dissociation of the WFNA on the convective heat, transfer coefficient at pressures between 65 and 165 psia and temperatures up to 140 F is insignificant.

2 The preliminary investigations in the local boiling region indicate that the heat transfer rate may be increased at least 30 per cent over that obtained by forced convection. That increase in heat transfer rate, however, is accompanied by a lack of stability and an increase in the pressure drop across the test section.

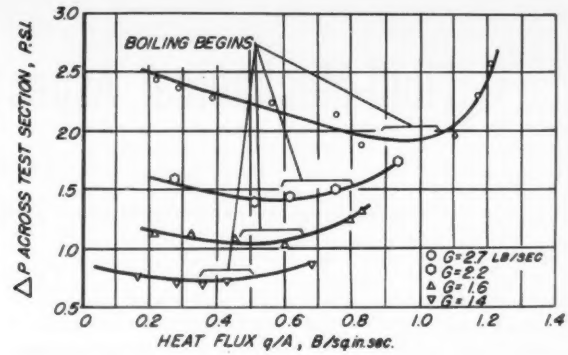

FIG. 17 THE EFFECT OF HEAT ADDITION ON FRICTIONAL PRESSURE DROP FOR CONVECTIVE AND BOILING HEAT TRANSFER. TEST SECTION, 0.539 IN. ID × 24 IN. LONG; INLET WFNA TEMPERATURE, 80 F; PRESSURE 65 PSIA

Acknowledgments

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The authors are indebted to Dr. M. J. Zucrow, project director, for his guidance in conducting the research work and for his counsel and assistance in preparing this article. Appreciation is also expressed to Dr. C. F. Warner for his continuous assistance and to the NACA staff of the Lewis Flight Propulsion Laboratory, Cleveland, Ohio, for their whole-hearted cooperation.

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(*Continued on page 236*)

Fluid-Mechanical Aspects of Flame Stabilization

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Flame stabilization in the wake of a bluff-body flame holder is visualized as a balance between the transport of cool, fresh gas into the wake zone by turbulent mixing and turbulent heat conduction within the wake from the zone of hot, chemically reacting gases. By considering the energy balance in the wake, it is shown that for fully premixed gases and turbulent wake flow, the blow-off velocity is proportional to the square of the turbulent normal burning velocity, linearly proportional to the maximum breadth of the flame holder, and inversely proportional to the turbulent mass transport coefficient. An explanation is offered for the fact that the "eddy recirculation" theory and the present wake mixing concept lead to similar results for the blow-off velocity. Attempts are now being made to extend the present approach to the case where the wake is partly laminar and partly turbulent.

Nomenclature

x	= distance along the wake axis, measured from the junction of regions 1 and 2
D	= diameter of rod flame holder
δ	= breadth of wake
ρ, p, u, H	= density, pressure, flow velocity, enthalpy, respectively
$\bar{m}$	= mass flux in wake, $\rho_w u_w \delta$
k	= turbulent mass transport coefficient across wake boundaries, appearing in relation $d\bar{m}/dx = k\rho_e u_e$
ϵ_H	= turbulent enthalpy exchange coefficient
ν	= kinematic viscosity
Q	= heating value of gas mixture
ϵ	= concentration of products
V_{BO}	= blow-off velocity
S_T	= normal turbulent burning velocity

Subscripts

e	= quantities in the unburned mixture outside the wake
w	= quantities within the wake, averaged across the wake
i	= ignition temperature (or enthalpy)

Introduction

IN THE present state of our knowledge about flame stabilization in the wake of bluff-body flame holders, it seems desirable to explore various extreme points of view in order to bring out the most important physical factors. This paper is concerned almost exclusively with the fluid-mechanical aspects of the problem for fully premixed gas mixtures at Reynolds numbers sufficiently high so that the flow in the wake is fully turbulent. Flame stabilization is visualized as a balance between two competing sources of energy transfer: (a) transport of cool, fresh gas into the wake zone by turbulent mixing across the wake boundaries; (b) turbulent transport of heat energy, or turbulent heat conduction, within the wake zone parallel to the wake boundaries from the hotter portion to the cooler fresh gas. Since the rate of mass transport into the wake increases very nearly linearly with the flow velocity of the unburned mixture, a characteristic velocity must eventually be reached at which cool mixture is transported into the wake at a rate that exceeds the ability of turbulent heat conduction to bring the mixture up to its ignition temperature—in other words, the flame "blows out."

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Analysis

In order to simplify the analysis the wake region is divided into two distinct zones: (a) a precombustion zone in which the reaction rate is negligible and heat conduction predominates; (b) a combustion zone in which heat conduction is negligible (see Fig. 1). The flame holder is a long cylindrical

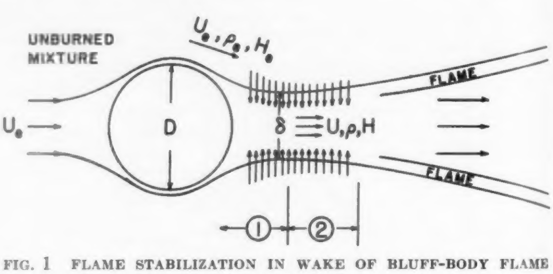

FIG. 1 FLAME STABILIZATION IN WAKE OF BLUFF-BODY FLAME HOLDER

rod transverse to the main flow direction, and the influence of other solid boundaries is ignored for the moment.

Energy Balance

Zone 1—Heat Conduction, No Combustion

Since the initial axial mass flow in the wake just at the flame holder is zero, the energy balance in this zone yields the following relation at any station

$$\delta \rho_w \epsilon_H \frac{dH_w}{dx} = \rho_w u_w \delta (H_w - H_e) \qquad [1]$$

or

$$\frac{dH_w}{dx} = \frac{u_w}{\epsilon_H}(H_w - H_e) \qquad [1a]$$

Zone 2—Combustion (Heat Conduction Negligible)

In this zone the rate of increase of enthalpy along the wake axis is equal to the rate at which heat is generated by the reaction (the usual term), plus the rate of enthalpy transport across the wake boundaries, i.e.,

$$\frac{d}{dx}(m\, H_w) = H_e \frac{d\bar{m}}{dx} + \bar{m}\, Q \frac{d\epsilon}{dx} \qquad [2]$$

or

$$\bar{m}\frac{dH_w}{dx} + (H_w - H_e)\frac{d\bar{m}}{dx} = \bar{m}\, Q \frac{d\epsilon}{dx}$$

In other words, the chemical reaction must not only raise the temperature of the gas already contained in the wake, but

must also heat up the cool, fresh gas that is continually transported into the wake across the wake boundaries.

Now

$$\frac{d\epsilon}{dx} = \frac{1}{u}\frac{d\epsilon}{dt}, \quad \text{and} \quad \frac{d\bar{m}}{dx} = k\rho_e u_e$$

as in the mixing theory recently formulated for adiabatic flows by L. Crocco and the present author (1).[2] Therefore

$$\frac{dH_w}{dx} = -(H_w - H_e)\frac{k}{\delta}\frac{\rho_e u_e}{\rho_w u_w} + \frac{Q}{u_w}\frac{d\epsilon}{dt} \quad [3]$$

At the junction of zones 1 and 2 the enthalpy and the enthalpy gradient must both be continuous, so that the expressions for H_w in Equations [1a] and [3] are identical at this station. This condition yields the important relation for the wake velocity

$$u_w^2 = \frac{\epsilon_H Q \dfrac{d\epsilon}{dt}}{(H_i - H_e)} - k\frac{T_i}{T_e}\frac{\epsilon_H}{\delta}u_e \quad [4]$$

But the first term on the right-hand side of Equation [4] is the expression for the square of the turbulent normal burning velocity in a purely "thermal flame theory," so that

$$u_w^2 = S_T^2 - k\, T_i/T_e \frac{\epsilon_H}{\delta}u_e \quad [5]$$

From this last equation, one sees that $u_w \rightarrow 0$ when u_e approaches a critical value that can be identified with the blow-off velocity. As the velocity of the unburned mixture approaches this limiting value, Equation [1a] shows that the preheating conduction zone in the wake extends to larger and larger distances behind the flame holder, i.e., the flame "blows away." From Equation [5] this critical or "blow-off" velocity is given by the expression

$$V_{BO} = \frac{S_T^2}{\epsilon_H}\frac{\delta}{kT_i/T_e} \quad [6]$$

But at high Reynolds numbers, $\delta \cong D$, and $\epsilon_H = a^2\nu$, where a is the ratio of turbulent to laminar heat-transfer (or momentum transfer) coefficients ($a \cong 10$). Finally, with $\nu_w/\nu_e = (T_w/T_e)^{1.75}$

$$V_{BO} \cong \frac{S_T^2 D}{k(T_i/T_e)^{2.75}}\frac{1}{a^2\nu_e} \quad [7]$$

i.e., the blow-off velocity at high Reynolds numbers is proportional to the square of the turbulent normal burning velocity, linearly proportional to the rod diameter, and inversely proportional to the mass transport coefficient. In nondimensional form

$$\frac{V_{BO}D}{\nu_e} \cong \frac{1}{k}\left(\frac{S_T D}{\nu_e}\right)^2 \frac{1}{a^2\ (T_i/T_e)^{2.75}} \quad [8]$$

By taking $a^2 = 100$, $T_i/T_e = 3.0$, and $k = 0.03$ (which appears to be a reasonable value for wake mixing), one obtains

$$\frac{V_{BO}D}{\nu_e} \cong 0.016\left(\frac{S_T D}{\nu_e}\right)^2 \quad [8a]$$

For a rod $^1/_4$ in. in diameter, with a turbulent normal burning velocity of about 15 ft/sec, the calculated blow-off velocity is about 480 ft/sec. This value is certainly of the correct order of magnitude, which is all that should be claimed for it at the present time. Of course the restriction to a cylindrical rod is not necessary, and in fact it may easily be verified that the analysis applies equally well to a three-dimensional bluff body. In general, D is some appropriate maximum body dimension normal to the flow direction.

Recently D. B. Spalding (2) investigated theoretically three different possible mechanisms of flame stabilization: recirculation in the wake, stabilization by standing cylindrical vortices, and "jet mixing." By means of dimensional arguments he shows that in each case $V_{BO} \sim D\rho S_u^2$, where S_u is the laminar normal burning velocity. But at high Reynolds numbers there may be some justification for the assumption that $S_T^2/S_u^2 \sim \epsilon_H/\nu = a^2$, in which case, Spalding's results and those of the present note are quite similar.

[2] Numbers in parentheses refer to the References on page 236.

Comparison Between Recirculation and Wake Mixing "Models"

At first it seems surprising that two physically different "models" of the flame-holding mechanism, such as recirculation and wake mixing, should lead to identical results for the blow-off velocity. But a closer study shows that these two mechanisms are formally identical just at blow-off. In the recirculation model a certain fraction of the fresh mixture is heated by contact along the wake boundaries with the hot, burned gases circulating in the eddy just behind the flame holder. This fraction is "trapped" in the eddy and reacts chemically while flowing back upstream along the wake axis. At blow-off the heat energy thus liberated is just sufficient to replace the energy lost by the burned gases in heating up the fresh mixture. In the wake-mixing model, on the other hand, a portion of the fresh mixture is transported across the wake boundaries and is brought up to the ignition temperature by turbulent heat conduction along the wake axis. However, just at blow-off, $(dH_w)/(dx) \rightarrow 0$, as shown by Equation [1a], and the amount of energy given up by the reaction zone to the preheating zone vanishes. By Equation [3] the heat generated by chemical reaction is equal to the heat lost in the mixing process, exactly as in the recirculation model.

In either case the expression for the blow-off velocity is derived very simply by equating the heat loss during mixing, equal to $(H_w - H_e)\ \Delta\dot{m}/\dot{m}$, with the heat generated by chemical reaction, which is given by $Q(d\epsilon)/(dt)\Delta t$, where $\Delta\dot{m}/\dot{m}$ is the fractional increment of fresh gas in the wake, and Δt is the time available for the reaction. Spalding (2) takes $\Delta\dot{m}/\dot{m}$ = constant and $\Delta t \sim D/V_{BO}$, i.e., the geometric flow pattern depends only upon the rod diameter and not on the velocity, in which case he obtains the result quoted above, namely that

$$V_{BO} \sim DQ\frac{d\epsilon}{dt}, \quad \text{or} \quad V_{BO} \sim \rho D S_u^2$$

In the present paper

$$\frac{\Delta\dot{m}}{\dot{m}} = \frac{k\rho_e u_e u_w \Delta t}{\rho_w u_w \delta} = k\frac{\rho_e}{\rho_w}\frac{u_e}{\delta}\Delta t$$

so that

$$V_{BO} \sim \frac{Q\dfrac{d\epsilon}{dt}}{(H_i - H_e)}\frac{D}{k}T_e/T_i$$

a result that is of course identical with Equation [6]. If the chemical reaction is of second order, then $d\epsilon/dt = B\rho_i f(T_i)$ and

$$V_{BO} \sim \frac{D\rho_e T_e}{k(H_i - H_e)}\frac{Q}{T_i^2}B$$

Future Work

When the wake is not fully turbulent but contains an initial laminar portion, then the flow geometry is no longer solely dependent on the rod diameter, and the wake breadth δ is not simply proportional to D. A closer examination of the fluid mechanical problem in this case is now being made. The present approximate treatment of flame stabilization

can also be extended to include diffusion of fuel and air of differing molecular weights.

Even in its present rather primitive form the analysis shows that any flame-holding device in which the turbulent mass transport rate is reduced, while heat is still supplied to the fresh mixture, will maintain the flame at much higher velocities than the conventional bluff-bodies. Such characteristics are expected to be shown (for example) by the streamlined body, "boundary-layer flame holder" proposed several years ago by Dr. H. S. Tsien, which is now being studied at the Jet Propulsion Laboratory, California Institute of Technology.

Acknowledgments

The author wishes to thank Drs. H. S. Tsien and Frank E. Marble for their stimulating discussions and valuable criticism.

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ARS Student Award Competition

Papers are now being invited for consideration for the 1954 student award. This award will be presented at the ARS Ninth Annual Convention in early December 1954. The competition is open to student members of the society.

The winning paper will be judged primarily on content, originality of thought, and effort. The subject scope should be within the broad field of jet and rocket propulsion as defined on the first page of this issue. Manuscript preparations should conform to the general instructions shown also on the first page.

Papers must be received not later than September 15, 1954, and should be clearly marked "Submitted for ARS Student Award Competition." Send papers to: The Secretary, American Rocket Society, 29 West 39th Street, New York 18, N. Y.

While every effort will be made to return the papers to the author, the Society will not assume any responsibility for the loss of manuscripts submitted in this competition. The decision of the Society in selecting a winner shall be final.

Ballistics of an Evaporating Droplet[1]

C. C. MIESSE[2]

Aerojet-General Corporation, Azusa, Calif.

The ballistics of an evaporating droplet is studied by assuming that (a) the drag coefficient varies inversely with the Reynolds number, (b) the surface area of the droplet varies linearly with time, and (c) the velocity of the surrounding gases varies linearly with distance. As a result of this analysis, the relationships between initial droplet velocity, air velocity, initial and final droplet diameter, physical properties of the droplet and of the surrounding air, and the dimensions of the chamber are determined. The analysis is applied to problems of upstream injection in a ramjet burner, spray-drying with countercurrent air flow and impingement-type spray collectors. A method for approximating nonlinear air velocities is given, and a method for determining the effective evaporation rate for droplets in an air stream is outlined.

Nomenclature

a = constant acceleration of droplet
B = physical property parameter
c_i = constant coefficients
C_D = drag coefficient
D = diameter of droplet
D_0 = initial diameter of droplet
f = function of s
F = force of drag; function of Y
g = acceleration of gravity; function of z
G = $(S/2)^2$
H = $(Z/2)^2$
I_n = modified Bessel function of first kind, nth order
J_n = Bessel function of first kind, nth order
k = $18\,\mu/\rho'$, viscosity parameter
K_n = modified Bessel function of second kind, nth order
L = length of chamber
L' = distance from injector to upstream reversal point
m = $0.3(\nu/\mathfrak{D})^{1/4}(|U - V|/\nu)^{1/2}$
M = $\pi\rho' D^3/6$, mass of droplet
p = $(U_0 - U_L)w/L\lambda$
P = $aL/4q^2U_L\,(U_L - U_0)$
q = k/λ
Q = $aL/4q^2U_L(U_0 - U_L)$
r = $(U_L - U_0)w/L = -p$
R = $|U - V|\,D/\nu$, Reynolds number
s = $2D\sqrt{q(U_L - U_0)/L\lambda}$
S = $2D_0\sqrt{q(U_L - U_0)/L\lambda}$
S' = $\pi D^2/4$, cross-sectional area of droplet
t = time
T = D_0^2/λ, lifetime of droplet
u = U/U_L
U = air velocity
U_0 = air velocity at $x = 0$
U_L = air velocity at $x = L$
v = V/U_L
v_0 = V_0/U_L
V = velocity of the droplet
V_0 = initial velocity of the droplet
w = D^2
W = D_0^2
x = distance downstream from injector
y = $w/W = D^2/D_0^2$
y' = value of y for $x = L$
Y = $\sqrt{D} + \lambda/m = \sqrt{D} + \alpha$
Y_n = Bessel function of second kind, nth order
z = $2D\sqrt{q(U_0 - U_L)/L\lambda}$
Z = $2D_0\sqrt{q(U_0 - U_L)/L\lambda}$
α = λ/m
λ = evaporation rate of droplet in still air
λ' = effective evaporation rate in air stream
μ = dynamic viscosity of air
ν = μ/ρ, kinematic viscosity of air
ρ = density of air
ρ' = density of liquid droplet
$\mathfrak{D}$ = diffusion coefficient of liquid droplet

Presented at the Joint ARS-IAS meeting, New York, January 30, 1954.

[1] The work reported in this paper was performed under the sponsorship of the Navy Department, Bureau of Aeronautics.

[2] Research Physicist, Liquid Engine Dept. Mem. ARS.

Introduction

THE associated phenomena of droplet evaporation and droplet ballastics are of great importance in all fields of engineering that are concerned with dispersions in gases: chemical engineering (spray drying); agricultural engineering (insecticides); combustion engineering (atomization of liquid fuels); and meteorology. One problem that is common to all of these fields is the determination of the relationship between the initial and final sizes of the droplets, the physical properties of the liquid and the surrounding gas, and the distance which the droplet travels. By assuming that the gaseous flow about the droplet is laminar, that the droplet evaporation is a diffusion-controlled process, and that the velocity of the surrounding gases varies linearly with distance, this problem can be solved analytically.

Analysis

Consider Newton's second law of motion, as applied to a spherical droplet

$$\frac{dV}{dt} = a + \frac{F}{M} = a + \frac{6F}{\pi\rho' D^3} \qquad [1]$$

where V = velocity of droplet
t = time
a = constant acceleration
F = force of drag
M = mass of droplet
ρ' = density of droplet
D = diameter of droplet

The drag force, F, can be represented by the equation

$$F = C_D \pi D^2 \rho (U - V)^2/8 \qquad [2]$$

where C_D = drag coefficient
ρ = air density
U = air velocity

For laminar flow ($R < 100$) the drag coefficient of a solid sphere can be expressed as

$$C_D = 24/R = 24\,\nu/(U - V)D \qquad [3]$$

where R = Reynolds number of the droplet
ν = kinematic viscosity of the air

This condition of laminar flow is satisfied in most practical

problems, since (for example) for a droplet of 200-micron diam moving in air, a relative velocity of 85 fps is permitted. Although liquid spheres do not follow the same law (see Fig. 1 of Reference 1 and Fig 55 of Reference 2), limits on the desired properties can be obtained by using different constants in Equation [3]. Substitution of Equations [2] and [3] into Equation [1] then yields

$$\frac{dV}{dt} = a + \frac{k(U - V)}{D^2} \qquad [4]$$

where $k = 18\,\mu/\rho'$, μ being the dynamic viscosity of the air.

The variation of droplet diameter due to evaporation has been established experimentally by Godsave (3)[3] (for still air) and by Ranz and Marshall (4) (for moving air) as

$$D^2 = D_0^2 - \lambda t \qquad [5]$$

where D_0 is the initial diameter of the droplet, and λ is the evaporation parameter.[4] Some typical variations of D^2 with t are shown in Fig. 1, from which it is apparent that this variation is linear, at least over the range of diameters considered. Since the minimum droplet diameter considered in these tests was about 400 microns, it is obvious that extrapolation of Equation [5] to smaller droplet sizes is necessary. The applicability of the following analysis will depend upon the validity of this extrapolation.

In order to consider the several possible linear variations of the air velocity, U, let

$$U = U_0 + (U_L - U_0)x/L \qquad [6]$$

Constant Air Velocity

For the case in which U_L is equal to U_0, let $w = D^2$ and

$$W = D_0^2 \qquad [9]$$

Substitution of Equations [9] and [5] into Equation [4] yields

$$w\frac{dV}{dw} = q(V - U_0) - \frac{aw}{\lambda} \qquad [10]$$

where $q = k/\lambda$. By imposing the boundary conditions of Equations [7] and [8] on the solution of Equation [10], the following equation for the velocity, V, is obtained

$$V = \left[V_0 - U_0 - \frac{aW}{\lambda(q-1)}\right]y^q + \frac{aW}{\lambda(q-1)}\,y + U_0 \text{ for } q \neq 1 \qquad [11]$$

where $y = w/W$. The corresponding equation for the displacement, x, can be determined by integration of Equation [11] as

$$x = \frac{W}{\lambda}\left[\frac{1}{q+1}\left(V_0 - U_0 - \frac{aW}{\lambda(q-1)}\right)(1 - y^{q+1}) + \frac{aW}{2\lambda(q-1)}(1 - y^2) + U_0(1 - y)\right] \qquad [12]$$

The relation between the original size, W, and the length of the chamber, L, can be determined by specifying the value, y', which the ratio y should have for $x = L$, and substituting these values into Equation [12]. By specifying that $y = 0$ for

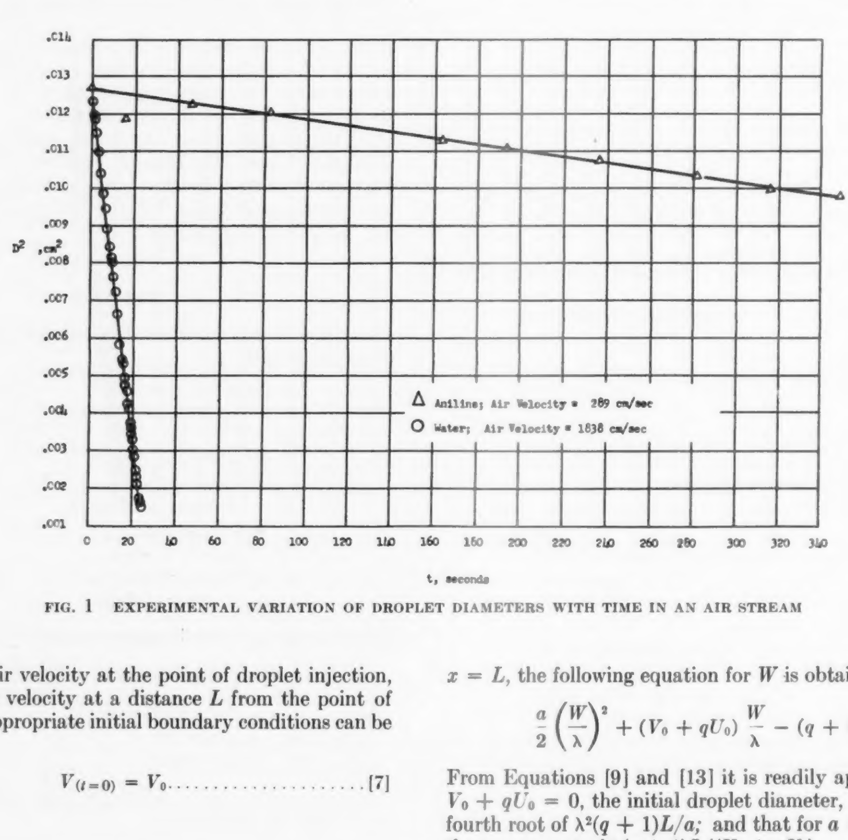

FIG. 1 EXPERIMENTAL VARIATION OF DROPLET DIAMETERS WITH TIME IN AN AIR STREAM

where U_0 is the air velocity at the point of droplet injection, and U_L is the air velocity at a distance L from the point of injection. The appropriate initial boundary conditions can be expressed as

$$V_{(t=0)} = V_0 \qquad [7]$$

and

$$D^2_{(t=0)} = D_0^2 \qquad [8]$$

$x = L$, the following equation for W is obtained

$$\frac{a}{2}\left(\frac{W}{\lambda}\right)^2 + (V_0 + qU_0)\frac{W}{\lambda} - (q+1)L = 0 \qquad [13]$$

From Equations [9] and [13] it is readily apparent that, for $V_0 + qU_0 = 0$, the initial droplet diameter, D_0, varies as the fourth root of $\lambda^2(q+1)L/a$; and that for $a = 0$, D_0 varies as the square root of $\lambda(q+1)L/(V_0 + qU_0)$.

Fig. 2 shows the variation of $V\lambda/aD_0^2$ with x/L for $U_0 = V_0 = 0$, and for various values of q. This variation corresponds to the velocity vs. distance profile of a free-falling droplet if

$$a = g(1 - \rho/\rho') \qquad [14]$$

[3] Numbers in parentheses refer to References on page 244.

[4] A method for determining the effect of air velocity on the evaporation parameter is given in the appendix to this paper.

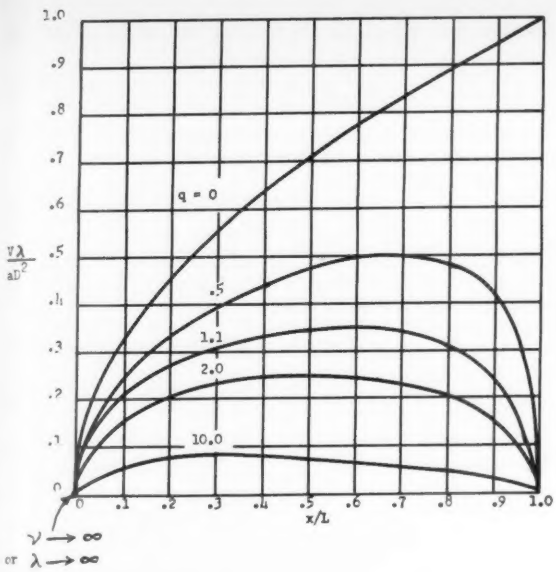

FIG. 2 VELOCITY VARIATION OF A FREE FALLING DROPLET FOR VARIOUS VALUES OF q

where g is the acceleration of gravity, and the term $(1 - \rho/\rho')$ is needed to account for the buoyancy effect (5). It is noted that the curve for $q = 0$, corresponding to an absence of viscous drag, corresponds directly to the velocity profile of a free-falling object when friction forces are neglected. The constant value of $V\lambda/aD_0^2 = 0$ occurs for $\lambda = 0$, and corresponds to the velocity profile of a free-falling solid body. The value of $V = 0$ for $x/L = 1$ for all values of q can be deduced from physical considerations, when it is realized that at this point the droplet will be completely evaporated, so that the remaining vapors will be traveling at the same velocity as the surrounding gases. Another point of interest on this figure is the singular point at the origin for either $\nu \to \infty$ or $\lambda \to \infty$. In the former case, no motion will occur, since the resistance to this motion is infinite. In the latter case, the droplet will evaporate immediately, and its vapors will then assume the same velocity as the surrounding air.

Fig. 3 shows the horizontal velocity variation of a droplet injected horizontally into still air ($U_0 = a = 0$). For $q = 0$, corresponding to zero viscosity of the air, the droplet retains its injection velocity until it is completely evaporated, at which time the vapors assume the velocity of the surrounding air. The curve for $q \to \infty$, corresponding to zero evaporation rate, can be obtained by considering D^2 as a constant in Equation [4]. Here again, there is a singular point at the origin for either $\nu \to \infty$ or $\lambda \to \infty$. The interpretation of this singular point is the same as that given above in connection with Fig. 2.

The variation of V/U_0 with x/L for various values of V_0 and q is shown in Fig. 4, where it is specified that $a = 0$ and $U_0 \neq 0$. From this figure, it is apparent that a droplet injected at the velocity of the surrounding air ($V_0/U_0 = 1$) will retain its injection velocity, regardless of the value of q. It is noted that for $q = 0$, corresponding to zero viscosity, the droplet will retain its original injection velocity until completely evaporated. The limit cases of $\nu \to \infty$ and $\lambda \to \infty$ result in a horizontal line at $V/U_0 = 1$, and a singular point at (0.1), respectively. For the case of zero evaporation rate, the solution of Equation [4] with D considered as constant shows immediately that $V/U_0 = 1$ only for $V_0/U_0 = 0$, or $x \to \infty$. Inspection of Fig. 4 reveals that the curves for $V_0 < 0$ and $q = 1$ are symmetric about the x/L axis. This symmetry for $q = 1$ can be derived analytically from Equations [11] and [12]: $x/L = WU_0(v^2 - v_0^2)/\lambda L(1 - v_0)$. This latter equation predicts that $x/L \leq 0$ for $q = 1$ and $v_0 \leq -1$.

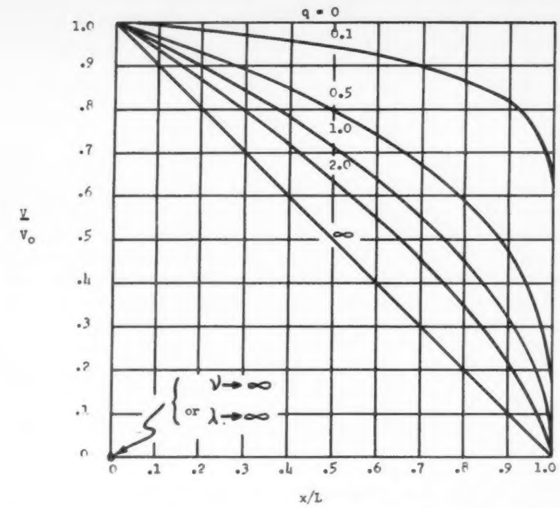

FIG. 3 VELOCITY VARIATIONS OF DROPLETS INJECTED INTO AIR AT REST, FOR VARIOUS VALUES OF q

Increasing Air Velocity (6)

Substitution of Equation [6] into Equation [4] yields the second-order differential equation for the displacement, x

$$D^2\left(\frac{d^2x}{dt^2} - a\right) = k\left(U_0 + \frac{U_L - U_0}{L}x - \frac{dx}{dt}\right) \ldots [15]$$

For $U_L > U_0$, let

$$s = 2D\sqrt{q(U_L - U_0)/L\lambda} \ldots\ldots\ldots\ldots [16]$$

and

$$u = U/U_L = s^{q+1}f(s) \ldots\ldots\ldots\ldots [17]$$

Substitution of Equations [16] and [17] into Equation [15] results in the following equation for $f(s)$

$$s^2f'' + sf' - [s^2 - (q+1)^2]f = Ps^{3-q} \ldots\ldots [18]$$

where $P = aL/4q^2U_L(U_L - U_0)$, and where the primes denote differentiation with respect to s.

Since Equation [18] is readily recognized as a nonhomo-

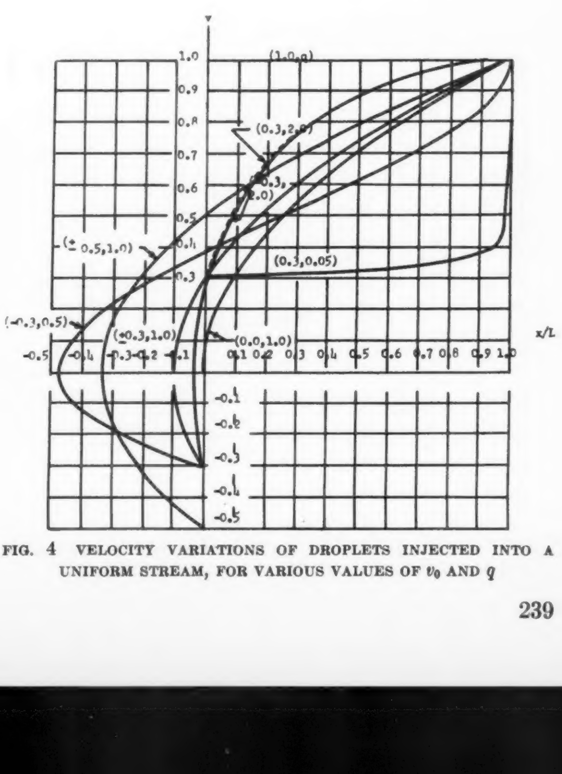

FIG. 4 VELOCITY VARIATIONS OF DROPLETS INJECTED INTO A UNIFORM STREAM, FOR VARIOUS VALUES OF v_0 AND q

geneous Bessel equation, its solution can be obtained by standard methods (7). The complete solution of Equation [15], for $U_L > U_0$, then becomes

$$u = s^{1+q}[c_1 I_{1+q}(s) + c_2 K_{1+q}(s)] - Ps^2 \{[sK_q(s) + 2K_{q-1}(s)]I_{q+1}(s) - [sI_q(s) - 2I_{q-1}(s)]K_{q+1}(s)\} \quad \text{[19]}$$

where $I_n(s)$ and $K_n(s)$ are modified Bessel functions of the first and second kinds, respectively, and the nth order.

In the following derivations, a and hence P will be set equal to zero, since the occurrence of a linearly increasing velocity in an acceleration field is held to be rare. With this simplification, the relative velocity of the droplet, $v = V/U_L$, can be expressed by the equation

$$v = -\frac{2q}{s}\frac{du}{ds} = 2qs^q[c_2K^q(s) - c_1I_q(s)] \quad \text{[20]}$$

By imposing the initial conditions on Equations [19] and [20], the equations for c_1 and c_2 are readily determined as

$$c_1 = [2qu_0K_q(S) - v_0SK_{1+q}(S)]/2qS^q \quad \text{[21]}$$

and

$$c_2 = [2qu_0I_q(S) + v_0SI_{1+q}(S)]/2qS^q \quad \text{[22]}$$

where $S = 2D_0\sqrt{q(U_L - U_0)/L\lambda}$.

It is interesting to note that Equation [11] (with $a = 0$) can be derived from Equations [20], [21], and [22], by letting $U_L = U_0$. By requiring that $s = 0$ for $x = L$, the equation for S (corresponding to the initial size of the droplet) can be written

$$S^q = 2^{q-1}(q-1)![2qu_0I_q(S) + v_0SI_{1+q}(S)] \quad \text{[23]}$$

Fig. 5 shows the variation of $S^2/4q$ with q for $u_0 = 0$, and for various values of v_0. The value of $S^2/4q$ for $q = 0$ can be determined from Equations [4], [5], and [14], which reveal that

$$\left(\frac{S^2}{4q}\right)_{(q=0)} = \frac{1-u_0}{v_0} \quad \text{[24]}$$

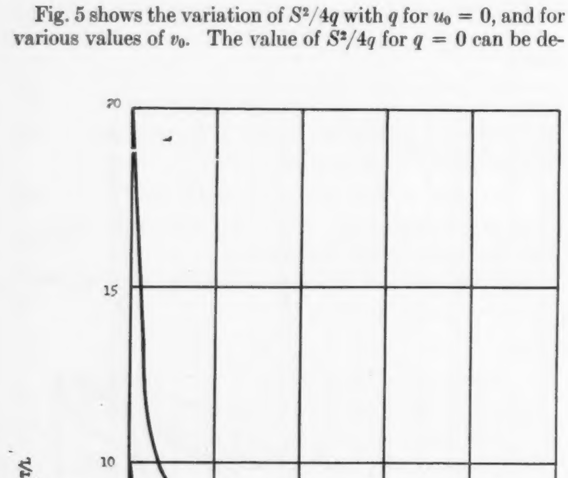

FIG. 5 VARIATION OF INITIAL DROPLET DIAMETER WITH q FOR VARIOUS VALUES OF v_0 (INCREASING AIR VELOCITY)

For small values of q, the desired expressions for V and for S can be obtained by defining the variable

$$r = \frac{(U_L - U_0)w}{L\lambda} \quad \text{[25]}$$

Substitution of Equation [25] into Equation [10] and differentiation of the resulting equation with respect to r yields the following equation for $V(r)$

$$rV'' + (1 - q)V' = qV \quad \text{[26]}$$

Since q is assumed to be small, V may be expressed as a perturbation series $V = V^{(0)} + qV^{(1)} + q^2V^{(2)} + \ldots$ [27]

Substitution of Equation [27] into Equation [26] then yields the following equation for V (up to the second order in q)

$$V = c_3r^q\left[1 + \frac{qr}{1+q} + \frac{q^2r^2}{2(1+q)(2+q)}\right] + c_4\left[1 + \frac{qr}{1-q} + \frac{q^2r^2}{q(1-q)(2-q)}\right] \quad \text{[28]}$$

By requiring again that w (and hence r) is zero for $x = L$, the final equation for determining the initial diameter, D_0, for given values of q and v_0, is then determined as

$$(1 + u_0)q = G + \frac{G^2}{2(1-q)} + \frac{G^3}{6(1-q)(2-q)} - \left[\frac{1 + \frac{G}{1-q} + \frac{G^2}{2(1-q)(2-q)} - v_0}{1 + \frac{G}{1+q} + \frac{G^2}{2(1+q)(2+q)}}\right] \times \left[\frac{G}{q+1} + \frac{G^2}{(1+q)(2+q)} + \frac{G^3}{2(1+q)(2+q)(3+q)}\right] \quad \text{[29]}$$

where $G = (S/2)^2$.

Fig. 6 shows the variation of $v = V/U_L$ with x/L for $U_0 = 0$, $s_{(x=L)} = 0$, and for various values of v_0 and q. Here it is noted again that, for zero viscosity, the v versus x/L curve becomes a horizontal line, and that there is a singular point at the origin for $\nu \to \infty$, $\lambda \to \infty$, or for $v_0 = 0$.

Decreasing Air Velocity

For the case in which U_L is less than U_0, let

$$z = 2D\sqrt{q(U_0 - U_L)/L\lambda} \quad \text{[30]}$$

A derivation identical to that presented above in Equations [17] through [19] leads to the following complete equation for u

$$u = z^{1+q}[c_5J_{1+q}(z) + c_6Y_{1+q}(z)] - Qz^2\{[zY_q(z) + 2Y_{q-1}(z)]J_{1+q}(z) - [zJ_q(z) + 2J_{q-1}(z)]Y_{1+q}(z)\} \quad \text{[31]}$$

where $Q = aL/4q^2\, U_L(U_0 - U_L)$. For $a = Q = 0$, consideration of Equations [7], [8], and [31] leads to the following equations for the relative velocity, $v = V/U_L$, and for the constants c_5 and c_6

$$v = 2qz^q\,[c_5J_q(z) + c_6Y_q(z)] \quad \text{[32]}$$

$$c_5 = \frac{\pi}{2Z^q}\left[u_0Y_q(Z) - \frac{v_0}{2q}ZY_{1+q}(Z)\right] \quad \text{[33]}$$

$$c_6 = \frac{\pi}{2Z^q}\left[\frac{v_0}{2q}ZJ_{1+q}(Z) - u_0J_q(Z)\right] \quad \text{[34]}$$

where

$$Z = 2D_0\sqrt{q(U_0 - U_L)/L\lambda}$$

By requiring that $z = 0$ for $x = L$, the equation for determining Z can be written

$$Z^q = 2^{q-1}(q-1)![2qu_0J_q(Z) - v_0ZJ_{q+1}(Z)] \quad \ldots\ldots [35]$$

For $q = 0$, it is readily determined that

$$\left(\frac{Z^2}{4q}\right)_{(q=0)} = \frac{u_0 - 1}{v_0} \quad \ldots\ldots\ldots\ldots\ldots [36]$$

For $q \ll 1$, a derivation similar to that presented above in Equations [25] through [29] leads to the following equations for V and $H = (Z/2)^2$, up to the first order in q

$$V = c_7p^q\left(1 - \frac{qp}{1+q}\right) + 1 - \frac{qp}{1-q} \quad \ldots\ldots\ldots [37]$$

and

$$q(u_0 - 1) = H - \frac{H^2}{2(1-q)} - \left[1 - \frac{v_0}{1 - \frac{H}{1+q}}\right]\left[\frac{H}{1+q} - \frac{H^2}{(1+q)(2+q)}\right] \ldots [38]$$

where

$$p = \frac{(U_0 - U_L)w}{L\lambda} \quad \ldots\ldots\ldots\ldots\ldots\ldots [39]$$

Fig. 7 shows the variation of $Z^2/4q$ with q for $u_0 = 2$, and for various values of v_0. It is interesting to note the similarity between this figure and Fig. 5. The variation of v with x/L for $u_0 = 2$, and for various values of v_0 and q, is shown in Fig. 8. Here again the horizontal line, representing constant (injection) velocity, is noted for $\nu = 0$. The singular point at the origin occurs only for $\lambda \to \infty$, on this figure, as the case of infinite viscosity is represented by a straight line coinciding with the air-velocity (u) curve.

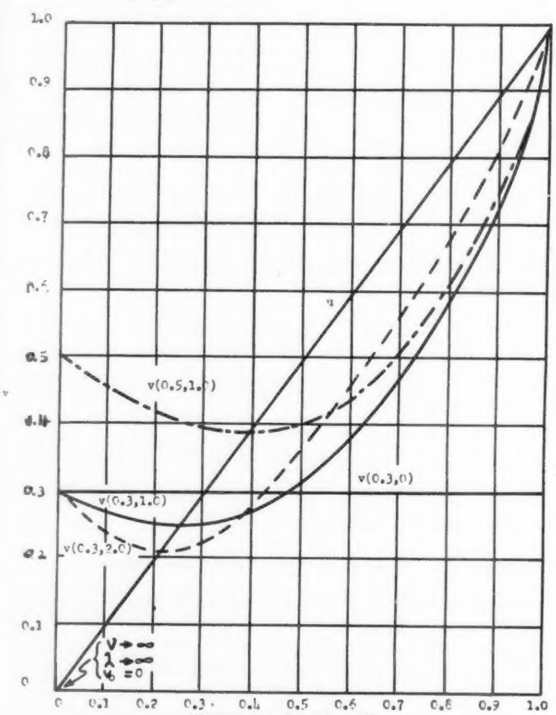

FIG. 6 VELOCITY VARIATION OF AN EVAPORATING DROPLET INJECTED INTO AN AIR STREAM OF INCREASING VELOCITY

Examples

Example 1: Upstream Injection in a Ramjet Burner

For this case, the air velocity can be considered as essentially constant, gravity effects can be neglected, and the

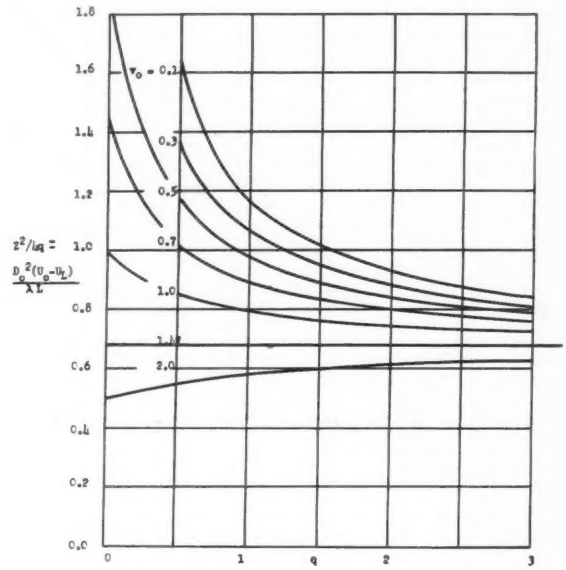

FIG. 7 VARIATION OF INITIAL DROPLET DIAMETER WITH q FOR VARIOUS VALUES OF v_0 (DECREASING AIR VELOCITY)

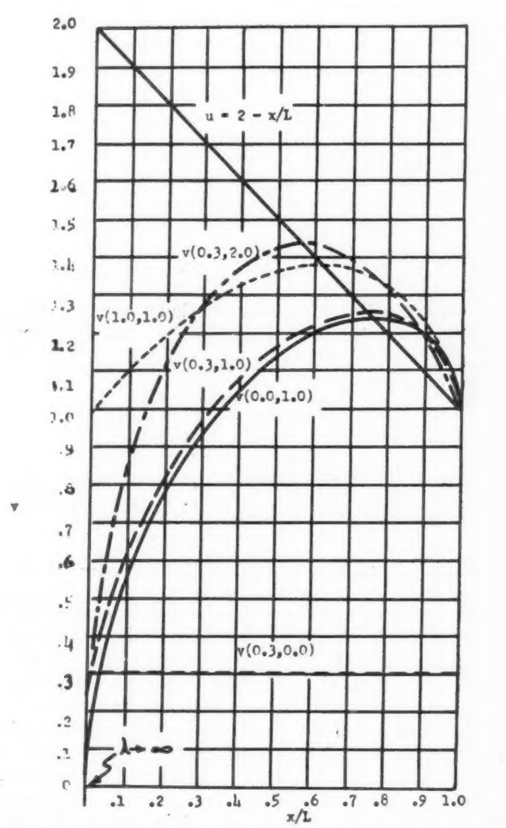

FIG. 8 VELOCITY VARIATION OF AN EVAPORATING DROPLET INJECTED INTO AN AIR STREAM OF DECREASING VELOCITY

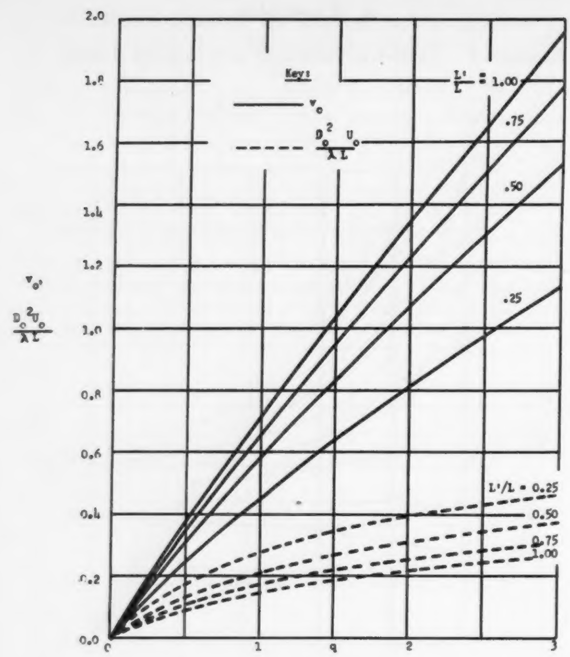

FIG. 9 VARIATION OF UPSTREAM INJECTION PARAMETERS WITH q FOR VARIOUS VALUES OF L'/L.

initial velocity, V_0, will be negative. The problem becomes one of determining the size of droplet which (a) will reverse its direction in a given distance, L', upstream of the injector, and (b) will be completely evaporated by the time it reaches the flame-holder at a distance, L, downstream of the injector. Substitution of zero for V in Equation [11] and of the resultant value y' thus determined for y, and of $-L'$ for x, in Equation [12] yields the following equation for satisfaction of the first condition above

$$\frac{D_0^2U_0}{L'\lambda} = \frac{q+1}{-\frac{V_0}{U_0} - q + q\left(1-\frac{V_0}{U_0}\right)^{-1/q}} \quad \ldots\ldots[40]$$

The second condition is satisfied by Equation [13], with $a = 0$. Simultaneous solution of Equations [13] and [40] then leads to a unique relationship between the initial velocity, V_0, and the evaporation parameter, q

$$\frac{V_0}{U_0}(L'/L+1) + q\left[L'/L + 1 - \left(1-\frac{V_0}{U_0}\right)^{-1/q}\right] = 0 \ldots[41]$$

The corresponding drop size, D_0, can be determined from Equation [40]. These relations are shown graphically in Fig. 9.

Example 2: Spray-Drying with Countercurrent Air Flow

The problem, in this case, is to determine the size of injected droplet which will be completely evaporated and which will have essentially zero velocity within a given distance, L, of vertical fall. Since "complete evaporation," in this instance, means merely complete vaporization of the liquid solvent with a remaining spherical shell of crystallized residue, the final diameter will not be zero. Since the resultant sphere has a hollow core, some allowance must be made for evaporation of the liquid inside this shell when the "final diameter" is determined. Substitution of zero for V and a negative value for U_0 (since U_0 and V_0 are in opposite directions) in Equation [11] yields the following equation for

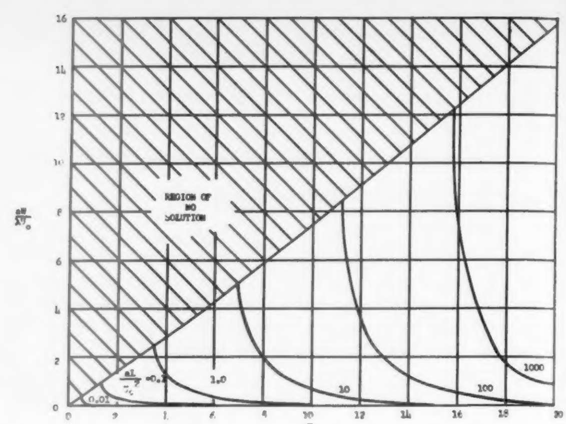

FIG. 10 VARIATION OF SPRAY-DRYING PARAMETERS WITH q.

the proper initial jet velocity, V_0

$$V_0/U_0 = v_0' = \frac{aW}{\lambda U_0(q-1)} - 1 - y'^{-q}\left[\frac{aW}{\lambda U_0(q-1)}\, y' - 1\right] \ldots[42]$$

where y' is the square of the adjusted diameter of the residue shell. The final equation for determination of the proper initial drop size, $D_0 = \sqrt{W}$, is then obtained by substituting Equation [42] into Equation [12]

$$\frac{1}{2(q-1)}\left(\frac{aW}{\lambda U_0}\right)^2\left[1 - y'^2 - \frac{2y'^{1-q}}{q+1}(1-y'^{q+1})\right] + \left(\frac{aW}{\lambda U_0}\right)\left[y' - 1 + \frac{y'^{-q}}{q+1}(1-y'^{q+1})\right] - \frac{aL}{U_0^2} = 0 \ldots[43]$$

The variation of $aW/U_0\lambda$ with q for various values of aL/U_0^2 is shown in Fig. 10, where y' is set at 0.6. Inspection of this figure reveals that for each value of q there is a maximum value of both $aW/\lambda U_0$ and aL/U_0^2 for which a solution is possible, thus prescribing a range of permissible values of aL/U_0^2 for each value of q. For large values of q (low evaporation rates), the boundary of the permissible region can be determined from the equation

$$\frac{aW}{\lambda U_0} = 5(q-1)/6$$

and the corresponding maximum values of aL/U_0^2 from the equation

$$\frac{aL}{U_0^2} = 5(0.6)^{-q}/6$$

For $aL/U_0^2 \ll (0.6)^{-q}$, the equation for the initial drop size, D_0, can be written

$$D_0^2 = \frac{\lambda L}{U_0}\left(\frac{1+q}{2}\right)(0.6)^q$$

which is a very convenient formula for determining the proper relation between the governing variables.

Example 3: Impinging-Type Spray Collectors

Since the technique of spray analysis frequently involves the injection of a liquid spray into a gas stream which impinges normally upon a flat plate on which the liquid droplets are collected, it is of considerable value to determine the amount of evaporation which takes place from the point of injection to the point of collection. The component of gas velocity normal to the plate can be approximated roughly by Equation [6], with $U_L = 0$. From Equations [31], [33], and [34] it

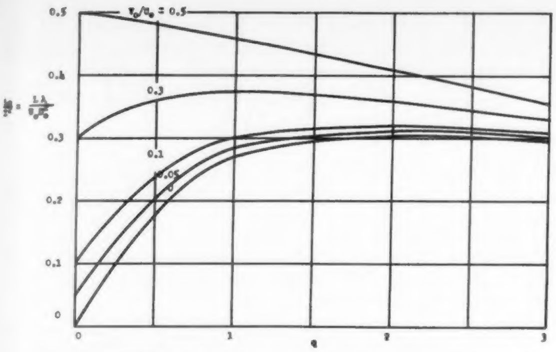

FIG. 11 VARIATION OF INITIAL DROPLET DIAMETER WITH q FOR NORMAL IMPINGEMENT OF AN AIR STREAM

can be determined readily that the relation between the dimensionless size of droplet, Z', collected on the plate and the dimensionless size of injected droplet, Z, can be expressed by the equation

$$\frac{J_{q+1}(Z')}{Y_{q+1}(Z')} = \frac{2U_0J_q(Z) - V_0ZJ_{q+1}(Z)}{2U_0Y_q(Z) - V_0ZY_{q+1}(Z)} \quad \text{[44]}$$

The equation for the dimensionless size of the largest droplet which will evaporate completely before striking the plate can be determined from the above equation by setting Z' equal to zero. Fig. 11 shows the corresponding variation of $4q/Z^2$ with q for various values of V_0/U_0.

Example 4: Piecewise Linear Air-Velocity Distribution

For many practical problems involving evaporation or burning of liquids injected into a gas stream, the variation of gas velocity is definitely nonlinear. Such cases suggest the use of a series of straight lines, rather than a single line, to approximate an experimental nonlinear velocity distribution. In order to investigate the advisability of such a piecewise linear approximation, consider the nonlinear gas velocity distribution that is approximated by two straight lines in Fig. 12. The equation for the relative gas velocity can be written

$$u_1 = 3x/2 \text{ for } 0 \leq x/L \leq 0.4 \quad \text{[45]}$$

and

$$u_2 = 0.6 + 2(x/L - 0.4)/3 \text{ for } 0.4 \leq x/L \leq 1.0 \quad \text{[46]}$$

The corresponding expressions for z become

$$z_1 = 2D\sqrt{3U_Lq/2\lambda L} \quad \text{[47]}$$

and

$$z_2 = 2D\sqrt{2U_Lq/3\lambda L} = 2z_1/3 \quad \text{[48]}$$

Substitution of the appropriate conditions

$$z_{(x=0)} = Z_1$$
$$z_{(x=0.4L)} = Z_2$$

and

$$z_{(x=L)} = 0$$

into Equations [19] and [20], which assure complete vaporization of the droplets within the combustor length, L, leads to the following pair of simultaneous equations for Z_1 and Z_2

$$u^* = 0.6 = v_0Z_2^{q+1}[I_{q+1}(Z_1)K_{q+1}(Z_2) - K_{q+1}(Z_1)I_{q+1}(Z_2)]/2Z_1^{q-1} \quad \text{[49]}$$

and

$$(2Z_2/3)I_{q+1}(2Z_2/3)v_0Z_2^q[I_{q+1}(Z_1)K_q(Z_2)K_{q+1}(Z_1)I_q(Z_2)]/Z_1^{q-1} + 1.2qI_q(2Z_2/3) = \pi(2Z_2/3)^q/2^{q-1}(q-1)! \quad \text{[50]}$$

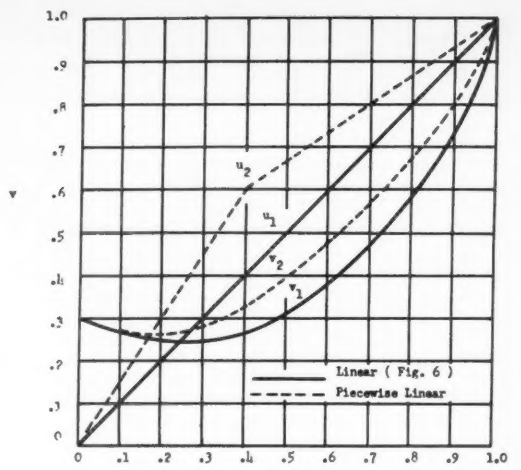

FIG. 12 VELOCITY VARIATION OF AN EVAPORATING DROPLET INJECTED INTO A PIECEWISE LINEAR AIR STREAM OF INCREASING VELOCITY

Fig. 12 shows a comparison of the velocity profiles obtained for $v_0 = 0.3$ and for $q = 1.0$ by using the piecewise linear distribution, above, with that obtained by using a simple linear velocity distribution (see Fig. 6). Since the corresponding values of Z are 3.16 and 3.38, respectively, it is evident that the negligible difference in final results does not warrant the great amount of labor involved in solving Equations [49] and [50] for the piecewise linear approximation.

APPENDIX

Burning Rate in a Gas Stream

Because of the scarcity of experimental data on the variation of diameter for burning droplets in a gas stream, some method must be devised for determining this variation from the known burning rate in still air. Since Ranz and Marshall (4) succeeded in obtaining experimental confirmation for Frössling's (8) evaporation equation, in determining the proper values for the constants (for water, benzene, and aniline) it should be possible to determine the evaporation rate in a gas stream from this equation. Frössling's equation can be written as

$$B\frac{dD^2}{dt} = -\left[2 + 0.6\left(\frac{\nu}{\mathfrak{D}}\right)^{1/3}\left(\frac{D|U - V|}{\nu}\right)^{1/2}\right]_1 \quad \text{[51]}$$

where B is a function of the physical properties of the droplet and of its vapor, and $\mathfrak{D}$ is the diffusion coefficient for the vapor. For still air, the last term of Equation [51] vanishes, so that the evaporation constant, λ, then becomes

$$\lambda = 2/B \quad \text{[52]}$$

Substitution of Equation [52] into Equation [51] yields

$$\frac{dD^2}{dt} = -\lambda\left[1 + 0.3\left(\frac{\nu}{\mathfrak{D}}\right)^{1/3}\left(\frac{|U - V|}{\nu}\right)^{1/2}D^{1/2}\right] = -(\lambda + m\sqrt{D}) \quad \text{[53]}$$

The solution of Equation [53] is readily determined as

$$F(Y) = 2Y^3 - 9\alpha Y^2 + 18\alpha^2Y + 6\alpha^3\ln(Y) = 3mt/2 + F(Y_0) \quad \text{[54]}$$

where

$$Y = \sqrt{D} + \lambda/m = \sqrt{D} + \alpha \quad \text{[55]}$$

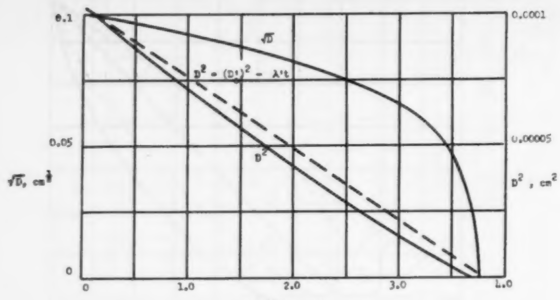

FIG. 13 VARIATION OF $\sqrt{D}$ AND OF D^2 WITH t IN A UNIFORM STREAM.

The variation of $\sqrt{D}$ with t can be determined by Equations [39] and [40]. By plotting the corresponding values of D^2 against t, as is shown in Fig. 13, it becomes apparent that the variation of D^2 with t is almost linear. Hence, the value of the "effective evaporation rate," λ', can be determined by the equation

$$\lambda' = \frac{(D_0')^2}{T} = \lambda \left(\frac{D_0'}{D_0}\right)^2 \qquad [56]$$

where D_0' is the value of D_0 which will satisfy Equation [54] for $D = 0$ and $t = T = D_0^2/\lambda$, the lifetime of the burning droplet. It is noted from Equation [51] that the presence of a gas stream will increase the evaporation rate, so that $\lambda' > \lambda$.

In order to make use of the above method to determine the maximum size of droplet in a combustion chamber, the approximate lifetime ($T = D_0^2/\lambda$) of the droplet is determined from the appropriate figure (5 or 7) by using the still-air value for λ, and the proper values of μ, ρ', v_0, U_L, and L. Then a first approximation for D_0' is determined by substituting D_0^2/λ for t, zero for D, and an appropriate value for $|U - V|$ (as indicated by the velocity profile) in Equations [53], [54], and [55]. This value of D_0', together with the corresponding values of D_0 and λ, can be used to determine a first approximation for λ' from Equation [56]. With this value of λ' (which leads to a lower value of the parameter q), a new value of the droplet lifetime, T, can be determined from the appropriate figure. Since a change in the velocity variation (due to the decrease in q) will bring about a change in the (average) relative velocity, $|U - V|$, and hence in the parameter, m, of Equation [53], it becomes necessary to determine a new average value, $|U - V|_{av}$ for the relative velocity. This value can be determined by the equation

$$|U - V|_{av} \approx (1/L) \int_0^L |U - V| dx \qquad [57]$$

where V is the droplet velocity corresponding to the effective evaporation constant, and where the integral is evaluated graphically by plotting U and V against x.

With the new values of λ', T, and m (as determined from the new value of $|U - V|_{av}$) second approximations for λ' and T can be found as before, and the process continued until two successive values of D_0' differ by less than a preassigned percentage.

If it is required to determine the effective evaporation rate of a droplet, the original size of which is given, over a distance in which the velocity of the surrounding air is constant, the following method can be used: By assuming $|U - V|_{av}$ to be relatively constant, Equation [51] can be written

$$\lambda' = \lambda\left[1 + m\sqrt{D_{av}}\right] = \lambda\left\{1 + m\sqrt{D_0}[(1 + y')/2]^{1/4}\right\} = \lambda h(y') \qquad [58]$$

where y' is the value of y for $x = L$. Substitution of L for x, λ' for λ, and y' (as given by Equation [58]) for y in Equation [12] yields the following equation for h

$$x = L = \frac{D_0^2}{\lambda h}\left\{2U_0\left[1 - \left(\frac{h-1}{m}\right)^4\right] - \frac{h|U_0 - V_0|}{h+1}\left(1 - \left[2\left(\frac{h-1}{m}\right)^4 - 1\right]^{\frac{h+1}{h}}\right)\right\} \qquad [59]$$

Solution of Equation [59] then gives the proper value of h, from which the corresponding values of y' and λ' can be determined from Equation [58].

With the new value of λ' thus determined, a new value for $|U - V|_{av}$ can be determined, and the whole process repeated until one value of λ' differs from the preceding value by a sufficiently small percentage.

Conclusions

As a result of this investigation, the following conclusions can be drawn:

1 By making several simplifying assumptions, it is possible to determine analytically the velocity profile of an evaporating droplet in a gas stream the velocity of which varies linearly with distance.

2 For a given nonaccelerating system, the maximum diameter of a droplet which will be completely evaporated in a given distance downstream of the injector varies directly as the square root of its evaporation rate. An increase in the velocity, either of the liquid jet or of the surrounding gas, will bring about a decrease in this maximum size, as could be expected.

3 Although the gas velocity affects the evaporation rate, it appears, both from theoretical considerations and from limited experimental evidence, that droplet evaporation in a gas stream can be described approximately by the same type of law as that which describes its evaporation in still air.

4 The approximation of a curved air-velocity profile by a series of straight lines instead of by a single chord is not warranted except in extreme instances.

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On the Burning of Single Drops of Fuel in an Oxidizing Atmosphere[1]

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A simplified model for the process of steady burning of a stationary droplet of fuel in an oxidizing atmosphere has been examined. Explicit expressions have been obtained for the burning rate of the fuel droplet, for the temperature at the flame front, and for the radius of the combustion surface. The principal assumptions on which our analysis is based are: the flame front is established at a spherical surface surrounding the drop; the rates of delivery of fuel and oxygen to this surface are in stoichiometric proportions; the rates of reaction at the flame front are fast compared to the rates of delivery of combustible gases. Our analysis is an extension and generalization of the work of G. A. E. Godsave. We are able to delete several of Godsave's restrictive assumptions by use of an efficient method for formulating the problem in which only integrated forms appear for the expressions of conservation of mass and energy. Our theoretical formulas provide a satisfactory correlation of Godsave's experimental results.

Nomenclature

r = radial distance from center of drop
T = temperature
T^* = standard reference temperature (usually 298.16 K)
t = time
ρ = density of gas mixture
ρ_l = density of liquid fuel
$(c_p)_K$ = specific heat at constant pressure of gaseous species K
c_l = specific heat of liquid fuel
λ = thermal conductivity
Δl = specific latent heat of vaporization of fuel
D_K = binary diffusion coefficient for species K
Y_K = weight fraction of species K in gaseous mixture
$\dot{m}_F$ = mass, rate of flow of fuel vapor
$(h_K)_T$ = specific enthalpy of species K at temperature T
γ_K = $\dot{m}_K/\dot{m}_F$, ratio of mass rate of flow of species K to the mass, rate of flow of fuel vapor
a, b = constants in the expression $(c_p)_F = a + bT$
δ_K = $(c_p)_K/(c_p)_O$, ratio of specific heat of species K to specific heat of oxidizer
χ_K = $\lambda/\rho D_K(c_p)_K$ = dimensionless parameter
K' = $2\dot{m}_F/\pi r_l \rho_l$ = "evaporation constant" defined by Godsave
$q^* - c_l(T_l - T^*)$ = standard heat of reaction for one gram of liquid fuel and γ_O gm of gaseous oxidizer, both initially at temperature T^*, forming H_2O and CO_2
α, β, ξ, Φ = computational parameters

Subscripts

O = oxidizer F = fuel vapor I = inert gas
o = condition in ambient gas ($r \to \infty$)
c = condition at combustion zone
l = condition at drop surface

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I Introduction

HETEROGENEOUS combustion is of importance in such widely different applications as stationary boilers, diesel engines, gas turbines, and rocket motors. In spite of the diversity of these machines, the combustion problems involved in their design bear marks of similarity. Numerous articles relating to heterogeneous combustion have been published, some of which are listed in the bibliography (1).[4]

The present preliminary theoretical investigations are restricted to the burning of single drops of fuel in an oxidizing atmosphere. Our theoretical results are used to correlate some experimental studies carried out by G. A. E. Godsave (2, 3). In technical combustion processes with little interference between burning droplets, the single-drop analysis may be a useful first approximation.

Experimental data on the burning of single drops of fuel have been published by Godsave (3) and Topps (4). Topps (4) studied the rate of burning of small fuel drops falling through a heated oxidizing atmosphere. Godsave (3) suspended small droplets on a fine quartz fiber and examined the burning droplet and the flame front as a function of time. In this way quantitative data were obtained for the rate of burning of the suspended droplet. Godsave (2, 5) obtained a successful interpretation of his results on the assumption that the chemical reaction rates do not control the rate of burning. This hypothesis simplifies the analytical treatment considerably.

Following Godsave (2), Spalding (6), and others, we postulate the following mechanism for the combustion processes: oxidizer is delivered from the surrounding atmosphere to the region of active combustion by convection and diffusion; the fuel evaporates and diffuses, without chemical change, to the reaction front, which is assumed to be a spherical shell surrounding the droplet. The location of the reaction front is defined by the condition that the ratio of the mass rate of delivery of fuel to oxidizer corresponds to stoichiometric proportions. It is assumed that the reactants are consumed instantaneously upon reaching the flame front. The problem of determining the rate of burning therefore reduces to finding the solutions of the appropriate transfer problems. Because it is to be expected that the rates of mass and heat transfer will be increased by the effects of convection, a lower limit for the burning rate will be obtained if the analysis is made for a droplet burning in a still atmosphere, by neglecting the convection of hot gases over the fuel droplet. Although fuel may be injected into the combustion chamber of an engine at a velocity appreciably different from the gas velocity in the

[4] Numbers in parentheses refer to References on page 251.
We have recently learned that extensive work on combustion and evaporation has been carried out in Japan in recent years. Some of the important papers are the following: "On the Evaporation Velocity of a Liquid Droplet in a High Temperature Gas," by Y. Tanasawa and K. Kobayashi, the Technology Reports of the Tohoku University, vol. XIV no. 2, 1950. "Experimental Study on Evaporation and Combustion of Fuel Droplet," by S. Kumagai and H. Isoda, *Science of Machine*, vol. 4, 1952, pp. 337–342. "Combustion of Fuel Droplets," by S. Kumagai and A. Kimura, *Science of Machine*, vol. 3, 1951, pp. 431–434.

chamber, it appears likely that, in some cases, the droplet is slowed down rapidly to the local gas velocity because of aerodynamic drag.

In the following Section II a theory for the burning of a droplet in a still atmosphere will be presented. The comparison of our theoretical results with the experimental studies of Godsave (3) is carried out in Section III. Our method of analysis differs from that of Godsave in that we utilize only integrated forms for the energy and continuity equations, thereby simplifying the analytical treatment, since only first-order differential equations occur. Because of the improvement in the method of formulating the problem, we are able to derive without difficulty an explicit expression for the mass rate of fuel flow without introducing the invalid approximations that the thermal conductivity and the specific heat of fuel vapor are independent of the temperature. Furthermore, we extend Godsave's analysis in two important respects by obtaining explicit expressions for (a) the temperature of the combustion surface, and (b) the radius of the combustion surface.

II A Simplified Model for the Burning of Single Drops of Fuel

For the sake of clarity we tabulate all of the important assumptions upon which our analysis is based. These are: 1 The droplets are spherical. 2 Convection effects may be neglected. 3 The flame front surrounding the drop is represented by a spherical surface concentric with the drop. All reactions take place instantaneously at this surface, at which the delivery rates of fuel and oxidizer are in stoichiometric proportions. 4 Steady-state conditions are assumed for fixed droplet sizes. This restriction greatly facilitates the mathematical treatment. It is reasonable to assume that the solution obtained for a fixed size applies to a drop decreasing in size when it reaches the radius used in the steady-state solution. 5 The effect of heat transfer by radiation is neglected. 6 Mean values will be used, when appropriate, for the physical properties. 7 The temperature of the liquid drop is assumed to be uniform and equal to the boiling temperature. Although this assumption is questionable (7), it does not exert a large effect on the theoretical results. 8 The pressure is assumed to be uniform throughout the system.

A schematic diagram of an evaporating and burning fuel droplet in an oxidizing atmosphere is shown in Fig. 1. The radius of the liquid drop is r_l and its temperature is the normal boiling point T_l. The radial distance of the combustion surface from the center of the liquid droplet is r_c and its temperature is T_c. The oxygen-inert gas mixture at a large distance from the combustion surface is at the temperature T_o. In order to clarify further our physical picture we show in Fig. 2a a plot of the temperature T as a function of the radial distance r from the center of the drop and, in Figs. 2b to 2d, diagrams of the weight fractions of fuel Y_F, oxidizer Y_O, and inert gas Y_I as a function of r. The data shown in Figs. 2a to 2d correspond to the burning of a droplet of benzene in air for $r_l = 0.005$ cm and $T_o = 300°$ K (compare Section III). The profile for the weight fraction of inert gas has been drawn on the assumption that the physical properties of combustion products and inert gas (in the oxidizer-inert gas mixture) are alike. If this assumption is not made, we must treat ternary gas mixtures both for $r < r_c$ and for $r > r_c$. This refinement can be introduced without difficulty but does not appear to be warranted in view of the crudeness of our model.

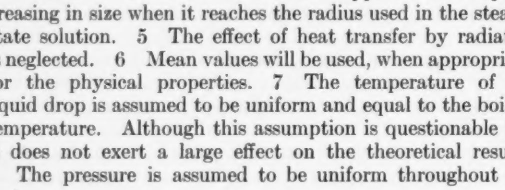

FIG. 1 SCHEMATIC DIAGRAM OF BURNING FUEL DROP

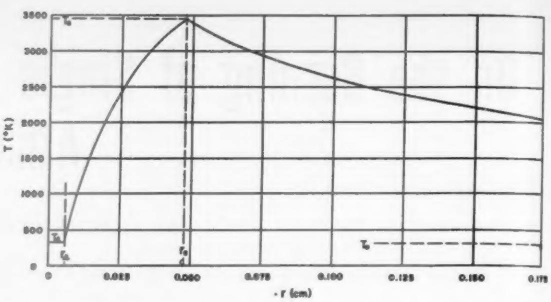

FIG. 2a TEMPERATURE (T) AS A FUNCTION OF DISTANCE FROM CENTER OF DROP (r) FOR 0.010 CM-DIAM BENZENE DROPLET BURNING IN AIR AT ATMOSPHERIC PRESSURE (UNCORRECTED FOR DISSOCIATION)

Let $\dot{m}_F$ represent the steady-state mass rate of fuel consumption, which is the desired eigenvalue of our boundary-value problem; t is the time; ρ, c_p, and λ represent, respectively, the density, specific heat at constant pressure, and thermal conductivity; Δl equals the specific latent heat of evaporation of the fuel.

For a constant-pressure flow process,[5] the first law of thermodynamics leads to the relation

$$dh/dt = dq/dt$$

where dh/dt is the rate of enthalpy increase of the gases passing through a fixed volume to which the total rate of energy transfer is dq/dt. For a spherical shell bounded by the radii r_i and r_f, the energy equation takes the following simple form

$$(dh/dt)_f - (dh/dt)_i = -\{[4\pi r^2\lambda(dT/dr)]_i - [4\pi r^2\lambda(dT/dr)]_f\} \quad [1]$$

Here the subscripts i and f identify, respectively, the surfaces at r_i and r_f.

The general continuity equation for species K can be written (8) in the form

$$\dot{m}_K = 4\pi r^2\rho Y_K[(\dot{m}_F/4\pi r^2\rho) - (D_K/Y_K)(dY_K/dr)] \quad [2]$$

where $\dot{m}_K$ is the rate of mass transport of species K, ρ is the density of the gas mixture, Y_K equals the weight fraction of species K, and D_K is the appropriate diffusion coefficient for species K. Equation [2] states that the total mass transport of species K is equal to the sum of the mass transport of species K associated with the movement of the average fluid, $Y_K\dot{m}_F$, and with mass transfer by diffusion, $-4\pi r^2\rho D_K(dY_K/dr)$.

[5] In our formulation we make no explicit use of the momentum equation. It is easily shown that the condition for conservation of momentum reduces to the statement that the pressure is practically constant, which we assume to be the case in the analysis.

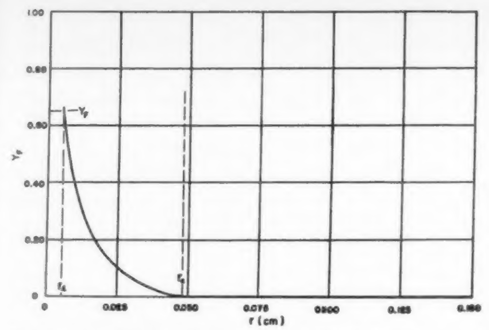

FIG. 2b WEIGHT FRACTION OF FUEL VAPOR (Y_F) AS FUNCTION OF DISTANCE FROM CENTER OF DROP (r) FOR 0.010 CM-DIAM BENZENE DROPLET BURNING IN AIR AT ATMOSPHERIC PRESSURE

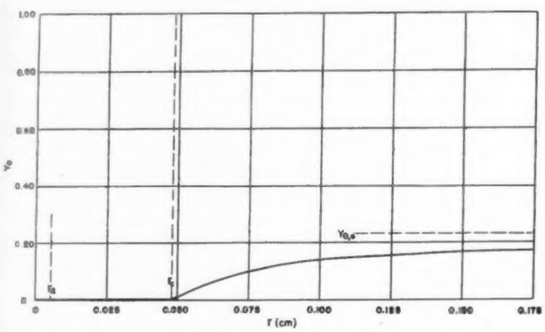

FIG. 2c WEIGHT FRACTION OF OXYGEN (Y_O) AS FUNCTION OF DISTANCE FROM CENTER OF DROP (r) FOR 0.010 CM-DIAM BENZENE DROPLET BURNING IN AIR AT ATMOSPHERIC PRESSURE

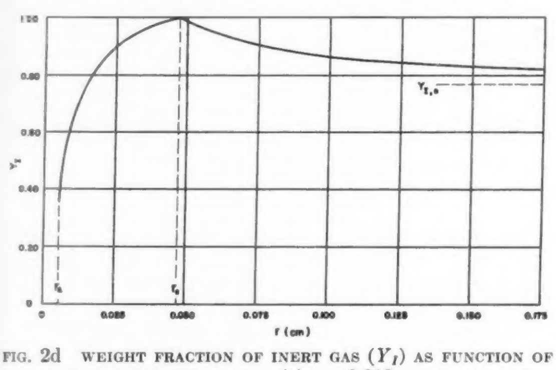

FIG. 2d WEIGHT FRACTION OF INERT GAS (Y_I) AS FUNCTION OF DISTANCE FROM CENTER OF DROP (r) FOR 0.010 CM-DIAM BENZENE DROPLET BURNING IN AIR AT ONE ATMOSPHERE

A Derivation of Godsave's (2) Equation for $\dot{m}_F$

We apply the expression for conservation of energy, which is given in Equation [1], to the spherical shell between r_l and r for $r < r_c$. The rate of enthalpy transport at r_l is

$$\dot{m}_F(h_F)_{Tl}$$

and at r

$$\dot{m}_F(h_F)_T$$

The rate of energy transport by thermal conduction at r_l is

$$-[4\pi r^2\lambda(dT/dr)]r_l = -\dot{m}_F\Delta l$$

and the rate of energy transport at r into the spherical shell between r_l and r is

$$4\pi r^2\lambda(dT/dr)$$

Hence Equation [1] becomes

$$\dot{m}_F[(h_F)_T - (h_F)_{Tl}] = -\dot{m}_F\Delta l + 4\pi r^2\lambda(dT/dr)$$

or

$$4\pi r^2(dT/dr) = (\dot{m}_F/\lambda)\left[\Delta l + \int_{T_l}^{T} (c_p)_F\, dT\right] \quad \text{[3]}$$

where the subscript F to the specific heat identifies the fuel vapor. If it is assumed that $\lambda = \lambda_1$ is independent of temperature, and also that $(c_p)_F = (c_p)_{F1}$ is constant, then Equation [3] becomes

$$4\pi r^2(dT/dr) = [\dot{m}_F(c_p)_{F1}/\lambda_1]\,\{[\Delta l/(c_p)_{F1}] + (T - T_l)\}$$

Integration of the preceding expression between the limits $r = r_l$ at $T = T_l$ and $r = r_c$ at $T = T_c$ leads directly to Godsave's equation for $\dot{m}_F$, viz.,

$$\dot{m}_F = \frac{4\pi\lambda_1}{(c_p)_{F1}}\,\frac{\ln\{1 + [(c_p)_{F1}(T_c - T_l)/\Delta l]\}}{[(1/r_l) - (1/r_c)]} \quad \text{[4]}$$

Reference to Equation [4] shows that for $r_c \gg r_l$, or for constant values of r_l/r_c, $\dot{m}_F$ is a linear function of the droplet radius. Furthermore, since T_c is generally large compared to T_l, it follows that $\dot{m}_F$ is not a sensitive function of T_l.

It should be noted that Equation [4] was derived without making any special assumptions about the location of the reaction front. For this reason the expression for $\dot{m}_F$ contains two unknown parameters, T_c and r_c. Godsave measured[6] r_c and showed that for reasonable, assumed values of T_c, an acceptable correlation for the measured values of $\dot{m}_F$ was provided by Equation [4].

B An Expression for $\dot{m}_F$ if λ and $(c_p)_F$ are Linear Functions of the Temperature

A refinement of Godsave's equation can be obtained without difficulty by deleting the assumptions (a) that λ can be assigned an average value λ_1 in the temperature interval between T_l and T_c, and (b) that the specific heat of the fuel vapor is constant. Thus we write the following approximate expressions

$$\lambda = \lambda_l(T/T_l) \quad \text{[5]}$$

where λ_l is the thermal conductivity of the fuel-inert gas mixture at the temperature T_l, and

$$(c_p)_F = a + bT \quad \text{[6]}$$

where a and b are suitably chosen constants. Equations [3], [5], and [6] lead to the result

$$4\pi r^2(dT/dr) = (\dot{m}_F T_l/\lambda_l T)\,[a(T - T_l) + (b/2)(T^2 - T_l^2) + \Delta l] \quad \text{[3a]}$$

Integration of the preceding expression from r_l, T_l, to r_c, T_c shows that

$$\dot{m}_F = \frac{4\pi\lambda_l r_l}{bT_l[1 - (r_l/r_c)]}\Bigg[\ln\{1 + [(T_c - T_l)/\Delta l] \times [a + (b/2)(T_c + T_l)]\} - \frac{a}{\xi} \times \ln\frac{(a + bT_c - \xi)(a + bT_l + \xi)}{(a + bT_c + \xi)(a + bT_l - \xi)}\Bigg] \quad \text{[7]}$$

where

$$\xi = \{a^2 - 2b[\Delta l - (b/2)T_l^2 - aT_l]\}^{1/2} \quad \text{[8]}$$

Reference to Equations [7] and [8] shows again that $\dot{m}_F$ is determined provided r_c and T_c are known. We shall show in paragraphs II-D and II-E that both T_c and r_c can be calculated by appropriate application of Equations [1] and [2] by utiliz-

[6] The experimental determination of r_c was greatly complicated by the fact that the combustion surface was far from spherical because of severe convections currents over the droplet.

ing the assumption that the delivery ratio of fuel to oxygen at the reaction front corresponds to the stoichiometric mixture ratio.

C Preliminary Remarks on the Use of Equations [1] and [2]

One of the objectives of the present analysis is to establish an efficient method for the utilization of the basic relations given in Equations [1] and [2]. It will be convenient to restrict the analysis to spherical shells located between r_l and $r > r_l$, or between r_c and $r > r_c$. In this case, simple explicit expressions are obtained for the rate of energy transport by thermal conduction through the surface of radius r. Thus Equation [1] leads to an expression of the form

$$4\pi r^2 \lambda (dT/dr) = \dot{m}_F (c_p)_K (\alpha + \beta T + \epsilon T^2) \qquad [9]$$

if the specific heat is a linear function of the temperature. Here the numerical values of α, β, and ϵ must be determined for each particular problem. Equation [2] becomes

$$4\pi r^2 \rho D_K (dY_K/dr) = \dot{m}_F (Y_K - \gamma_K) \qquad [10]$$

where

$$\gamma_K = \dot{m}_K / \dot{m}_F \qquad [11]$$

In the use of Equations [10] and [11], care must be taken to employ a positive value for γ_K if mass flow occurs in the same direction as the fuel transport, and to use a negative value for γ_K if mass flow occurs in the direction opposite to the direction of fuel transport.

It is evident by reference to Equations [9] and [10] that we can eliminate the radial distance as independent variable and write

$$\frac{dY_K}{Y_K - \gamma_K} = \chi_K \frac{dT}{\alpha + \beta T + \epsilon T^2} \qquad [12]$$

where the dimensionless parameter χ_K, which is not a sensitive function of pressure and temperature, and which is assumed to be independent of Y_K, is defined by the relation

$$\chi_K = \lambda / \rho D_K (c_p)_K \qquad [13]$$

A mean value is used for $(c_p)_K$ whereas λ, ρ, and D_K are computed at any conveniently chosen temperature. Integration of Equation [12] between $Y_O = 0$ at $r = r_c$ and $Y_O = T_{O,\,o}$ at $r = \infty$, corresponding to T_c and T_o, respectively, leads directly to the value of T_c for specified values of T_o and $Y_{O,\,o}$.[7] Similarly, integration between $Y_F = Y_{F,\,l}$ at $r = r_l$, $T = T_l$ and $Y_F = 0$ at $r = r_c$, $T = T_c$, gives an explicit approximate expression for $Y_{F,\,l} = 1 - Y_{I,l}$.[8]

In order to obtain the value of r_c we can utilize Equation [9] or Equation [10]. Equation [9] can be integrated directly between r_c, T_c and ∞, T_o, after expressing λ as a linear function of T. Introduction of the known relation for $\dot{m}_F$ into the resulting expression leads to an explicit relation for r_c. The integration of Equation [10] is somewhat more involved since ρD_K is a linear function of T to the same approximation that λ is a linear function of T. Hence integration of Equation [10] requires the determination of $T(r)$ prior to integration. We shall use Equation [9] for the determination of r_c.

By utilizing constant average specific heats only in the region $r > r_c$, it is to be expected that reasonable estimates, commensurate in accuracy with our assumed physical model, will be obtained for T_c, r_c, and $\dot{m}_F$.

D Determination of T_c and of $Y_{F,\,l}$

1 The Reaction Zone Temperature T_c

For the spherical shell between $r > r_c$ and r_c, Equation [1] becomes

$$\dot{m}_F[(1 + \gamma_O)(h_P)_T - \gamma_O)(h_O)_T] - \dot{m}_F [(1 + \gamma_O)(h_P)T_c - \gamma_O(h_O)_{T_c}] = 4\pi r^2 \lambda (dT/dr) - [4\pi r^2 \lambda (dT/dr)]_{r_c} \qquad [14]$$

where h_P and h_O denote, respectively, the specific enthalpies of products of reaction and of oxidizer. But $-[4\pi r^2\lambda(dT/dr)]_{r_c}$ equals the total heat evolved on reaction at T_c minus the energy transported to the fuel droplet, i.e.,

$$-[4\pi r^2 \lambda (dT/dr)]_{r_c} = \dot{m}_F \{ [(1 + \gamma_O)(h_P)_{T_c} + (h_F)_{T_c} + \gamma_O (h_O)_{T_c}] - \Delta l - [(h_F)_{T_c} - (h_F)_{T_l}] \}$$

where h_F is the specific enthalpy of the fuel vapor. Hence Equation [14] becomes

$$-4\pi r^2 \lambda (dT/dr) = \dot{m}_F \{ q^* + \gamma_O[(h_O)_T - (h_O)_{T^*}] - (1 + \gamma_O)[(h_P)_T - (h_P)_{T^*}] \} \qquad [15]$$

where[9]

$$q^* = -(1 + \gamma_O)(h_P)_{T^*} + (h_{F,\,l})_{T^*} + \gamma_O (h_O)_{T^*} + c_l (T_l - T^*) \qquad [16]$$

Here T^* is a standard reference temperature (usually chosen as 298.16° K), and c_l denotes a constant specific heat for the liquid fuel in the temperature range between T^* and T_l; the quantity q^* differs from the standard heat of combustion for 1 gm of liquid fuel through the addition of the term $c_l(T_l - T^*)$. If $(c_p)_P$ and $(c_p)_O$ are independent of the temperature, then Equation [15] reduces to the relation

$$-4\pi r^2 \lambda (dT/dr) = \dot{m}_F \{ q^* + (T - T^*) [\gamma_O (c_p)_O - (1 + \gamma_O)(c_p)_P] \} \qquad [15a]$$

Reference to Equation [15a] shows that it is of the form

$$4\pi r^2 \lambda (dT/dr) = \dot{m}_F (c_p)_O (\alpha + \beta T) \qquad [15b]$$

with

$$\alpha = -[q^*/(c_p)_O] - \beta T^* \qquad [17]$$

and

$$\beta = (1 + \gamma_O)\delta_P - \gamma_O \qquad [18]$$

where $\delta_K = (c_p)_K/(c_p)_O$.

From Equation [10] we can obtain the appropriate expression for the mass transfer of oxidizer

$$4\pi r^2 \rho D_O (dY_O/dr) = \dot{m}_F (Y_O + \gamma_O) \qquad [19]$$

where a negative sign has been used for γ_O because the oxidizer flows in a direction opposite to that of the fuel. Here D_O is the diffusion coefficient of oxidizer through the oxidizer-inert gas-combustion products mixture. Division of Equation [15b] by Equation [19] leads to the expression

$$\frac{dY_O}{Y_O + \gamma_O} = \chi_O \frac{dT}{\alpha + \beta T} \qquad [20]$$

where

$$\chi_O = \lambda / (c_p)_O D_O \rho$$

is a constant. Hence integration of Equation [20] between

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[7] The same result is obtained if we integrate Equation [12] from $Y_I = 1$ at $r = r_c$, $T = T_c$ to $Y_I = Y_{I,\,o} = 1 - Y_{O,\,o}$ at $r = \infty$, $T = T_o$.

[8] The same result is obtained if we integrate Equation [12] from $Y_{I,l}$ at $r = r_l$, $T = T_l$ to $Y_I = 1$ at $r = r_c$, $T = T_c$.

[9] For the present approximate calculations the heat release q^* and, therefore, T_c, r_c/r_l, and $\dot{m}_F$ are computed by neglecting the effect of dissociation of combustion products, fuel, and oxygen. The derived results would be expected to be roughly correct for gas mixtures leading to values of T_c well below 3000° K, i.e., for some hydrocarbon-air flames. The effect of dissociation on the calculated results can be incorporated into our present model by using an iteration procedure in which it is assumed that chemical equilibrium is established at every point. As the result of this refinement, the calculated values of T_c and of r_c/r_l are decreased by a first iteration; the temperature profile toward the oxidizer is flattened and the temperature raised because the reassociating gases act as a distributed heat source on recombination. The diffusive flow of oxygen inward is then increased, thereby leading to a further decrease of r_c/r_l. Rough calculations show that the net effect of dissociation on the calculated values of $\dot{m}_F$ for benzene-air flames is probably less than 10 per cent, although both T_c and r_c/r_l are decreased appreciably.

$Y_O = 0$, $T = T_c$ and $Y_O = Y_{O,o}$, T_o leads to the following explicit relation for T_c

$$T_c = \frac{\beta T_o - \alpha\{[1 + (Y_{O,o}/\gamma_O)]^{(\beta/\chi_O)} - 1\}}{\beta[1 + Y_{O,o}/\gamma_O]^{(\beta/\chi_O)}} \quad \ldots\ldots [21]$$

2 The Weight Fraction Profile of Fuel Vapor

It is evident from the formulation of the present problem that Y_F cannot equal unity at the droplet surface. For this reason it is of interest to estimate Y_F at r_l approximately.

From Equation [3a] and Equation [10], written in terms of the fuel, it follows that

$$\frac{dY_F}{Y_F - 1} = \frac{\lambda}{\rho D_F} \frac{dT}{(b/2)T^2 + aT + [\Delta l - aT_l - (b/2)T_l^2]} \quad \ldots [22]$$

where $\lambda/\rho D_F$ is independent of temperature and is assumed to be independent also of Y_F. Integration of Equation [22] between $Y_F = Y_{F,l}$ at $T = T_l$ and $Y_F = 0$ at $T = T_c$ leads to the result

$$Y_{F,l} = 1 - \frac{(a + bT_c - \xi)(a + bT_l + \xi)}{(a + bT_c + \xi)(a + bT_l - \xi)}^{-(\lambda/\rho D_F \xi)} \quad \ldots [23]$$

where ξ has been defined in Equation [8].

E Determination of the Combustion Radius

Equation [15b], which was derived on the assumption that the specific heats of oxidizer and inert gas are constant for $r > r_c$, may be used directly for the determination of r_c. After replacing λ by $\lambda_l(T/T_l)$ and integrating from r_c, T_c to ∞, T_o, the following relation is obtained

$$\frac{1}{r_c} = \frac{4\pi\lambda_l}{\dot{m}_F(c_p)_O T_l}\left[\frac{1}{\beta}(T_o - T_c) - \frac{\alpha}{\beta^2}\ln\frac{\alpha + \beta T_o}{\alpha + \beta T_c}\right] \quad \ldots [24]$$

where α and β are defined in Equations [16] and [17], respectively.

From Equations [7] and [24] we can now obtain an explicit expression for r_c/r_l. Thus we may write Equation [7] in the form

$$\dot{m}_F = \frac{4\pi\lambda_l r_l}{bT_l[1 - r_l/r_c]}\Phi \quad \ldots\ldots\ldots\ldots [7a]$$

where

$$\Phi = \ln\{1 + [(T_c - T_l)/\Delta l][a + (b/2)(T_c + T_l)]\} - \frac{a}{\xi}\ln\frac{(a + bT_c - \xi)(a + bT_l + \xi)}{(a + bT_c + \xi)(a + bT_l - \xi)} \quad \ldots [25]$$

From Equations [24] and [7a] it is seen that

$$\frac{r_c}{r_l} = 1 + \frac{(c_p)_O\Phi}{b}\left[\frac{1}{\beta}(T_o - T_c) - \frac{\alpha}{\beta^2}\ln\frac{\alpha + \beta T_o}{\alpha + \beta T_c}\right]^{-1} \quad \ldots [26]$$

Reference to Equation [26] shows the interesting result, which is in accord with some of the experimental observations, that r_c/r_l is a constant for fixed values of the physicochemical parameters. Hence Equation [7a] shows that $\dot{m}_F$ is a linear function of r_l.

The linear functional relation between $\dot{m}_F$ and r_l has been used by Godsave (3, 5) to obtain the following expression for the variation of droplet diameter with time

$$d^2 = d_0^2 - K't \quad \ldots\ldots\ldots\ldots [27]$$

Here d is the droplet diameter at time t, d_0 is the initial droplet diameter, and the evaporation constant K' is defined by the relation

$$K' = 2\dot{m}_F/\pi r_l \rho_l \quad \ldots\ldots\ldots\ldots [28]$$

Since K' is independent of r_l, it is a convenient parameter for comparing burning rates of different fuels for arbitrary droplet sizes.

III Comparison Between Calculated and Observed Results for the Burning of Single Droplets of Fuel

We have obtained in the preceding Section II a complete description for the burning of single droplets of fuel in an oxidizing atmosphere according to a simplified model. It is the purpose of the present discussion to compare calculated and observed values for r_c/r_l and for $K' = 2\dot{m}_F/\pi r_l \rho_l$.

The procedure for calculating various quantities, including r_c/r_l and K', involves the following steps: (a) For suitably chosen values of the physicochemical parameters we obtain T_c from Equation [21]. (b) The limiting weight fraction $Y_{F,l}$ is next obtained from Equation [23]. (c) The quantity r_c/r_l is given by Equation [26]. (d) Finally $2\dot{m}_F/\pi r_l \rho_l$ is calculated either from Equation [7] or from Equation [7a].

For the sake of completeness we have determined also the T vs. r and Y_K vs. r profiles for the burning of a benzene droplet in air if $T_o = 300° K$, $r_l = 0.005$ cm. The results of these calculations have been considered previously and are given in Figs. 2a to 2d.

A Summary of Calculated Results

The results of calculations for the burning of benzene, ethyl alcohol, ethyl benzene, n-heptane, and toluene in air are summarized in Table 1. Also listed in Table 1 are appropriate values of the physicochemical parameters, which were for the most part taken from Godsave's papers (3, 5).

B Comparison of Calculated and Observed Evaporation Constants

The calculated and observed evaporation constants are contrasted in Table 2. Reference to Table 2 shows satisfactory agreement between calculated and observed values of K' (and hence of $\dot{m}_F$). This result suggests that the physical model upon which the present analysis of burning of fuel drops is based represents a useful first approximation for the compounds considered. Unfortunately, experimental data are available only for fuels with very similar values of K'. For this reason the comparison between theory and experiment is not as stringent a test of the theory as might be desired. In particular, there are serious doubts that the basic physical assumptions involved in our model are applicable, for example, to the burning of an aniline droplet in nitrogen dioxide or in nitric acid vapors. Experimental studies on systems of this type will be carried out in our laboratory in the near future and compared with the results of the theoretical calculations.

TABLE 2 COMPARISON OF CALCULATED AND OBSERVED VALUES FOR THE EVAPORATION CONSTANT K'

Compound	Observed value of K', cm^2/sec	Calculated value of K', cm^2/sec
Benzene	0.0097	0.0100
Ethyl alcohol	0.0081	0.0079
Ethyl benzene	0.0086	0.0085
n-heptane	0.0097	0.0086
Toluene	(0.0066)	0.0087

We have recently carried out some theoretical calculations on the evaporation rate of pure compounds into still air by replacing T_c and T_l in Equation [4] by the known ambient and droplet temperatures, respectively. The results obtained for water droplets, on the assumption that $1/r_c \ll 1/r_l$, are in very satisfactory agreement with empirically determined values.

TABLE 1 PHYSICOCHEMICAL PARAMETERS AND CALCULATED VALUES FOR THE BURNING OF DROPS OF BENZENE, ETHYL ALCOHOL, ETHYL BENZENE, n-HEPTANE, AND TOLUENE IN AIR AT ATMOSPHERIC PRESSURE

FUEL	T_0, ° K	$\gamma_{O,0}$	γ_O	T_l, ° K	ρ_l, GM/CM^3	Δl, CAL/GM	a, CAL/GM-° K	b, CAL/GM-(° K)^2	λ_l, CAL/CM-SEC-° K	χ_O
Benzene	300	0.23	3.08	353	0.84	94.0	0.34	0.25×10^{-3}	55×16^{-6}	0.91
Ethyl alcohol	300	0.23	2.09	351	0.79	204	0.44	0.26×10^{-2}	55×10^{-6}	0.91
Ethyl benzene	300	0.23	3.07	409	0.84	81.0	0.40	0.25×10^{-3}	55×10^{-6}	0.91
n-Heptane	300	0.23	3.52	371	0.68	75.6	0.44	0.40×10^{-3}	55×10^{-6}	0.91
Toluene	300	0.23	3.13	384	0.84	87.0	0.37	0.25×10^{-3}	55×10^{-6}	0.91

FUEL	$(C_p)_O$, CAL/GM-° K	δ_P	T^*, ° K	q^*,[10] CAL/GM	β	α, ° K	T_c,[10] ° K	ξ, CAL/GM-° K	Φ	r_c/r_l[10]	K',[10] CM^2/SEC
Benzene	0.26	1.35	298	9,790	2.43	−38,400	3450	0.37	1.51	9.6	10.0×10^{-3}
Ethyl alcohol	0.26	1.58	298	6,460	2.79	−25,700	3100	0.42	1.05	5.3	7.9×10^{-3}
Ethyl benzene	0.26	1.35	298	9,850	2.43	−38,600	3470	0.46	1.48	9.3	8.5×10^{-3}
n-heptane	0.26	1.58	298	10,630	3.63	−42,200	3230	0.54	1.75	8.6	8.6×10^{-3}
Toluene	0.26	1.39	298	9,750	2.61	−38,300	3370	0.42	1.43	9.5	8.7×10^{-3}

[10] See footnote 9 for a discussion of the effect of dissociation on T_c and on r_c/r_l. For benzene T_c is decreased to about 2600° K when proper allowance is made for dissociation. The effect of dissociation on K' is probably small.

C Comparison of Observed and Calculated Values of r_c/r_l

Our theoretical analysis is based on the assumption that a spherical reaction surface surrounds the burning droplet. On the other hand, photographs of burning droplets indicate that the luminous region is of the form shown in Fig. 3. Godsave measured the diameter of the sphere corresponding to the dotted circle in Fig. 3 and stated that the ratio of this diameter to the droplet diameter is a constant, characteristic for the fuel, when burning in air.

The values of r_c/r_l calculated from Equation [26] are contrasted in Table 3 with the values of r_c/r_l deduced by Godsave from his photographs of burning fuel drops. Reference to Table 3 shows that the calculated values are appreciably larger than the observed data. There are several obvious reasons for the observed discrepancies. Thus reference to Fig. 3 shows that the "still" droplet was actually subjected to strong convection currents during burning; the value of r_c/r_l for a spherical surface with area equivalent to the area of the observed luminous zone is roughly double that of Godsave's tabulated values. Furthermore, it is not evident that the reaction surface in our idealized model should, in fact, be identified with the region of maximum luminosity. The surface for maximum temperature gradients, as determined from schlieren photographs (5), corresponds to larger "observed" values of r_c/r_l than are listed in Table 3.

TABLE 3 COMPARISON OF CALCULATED AND "OBSERVED" COMBUSTION RADII

Fuel	"Observed" values of r_c/r_l	Calculated values of r_c/r_l
Benzene	2.97	9.6
n-heptane	3.03	8.5
Toluene	2.59	9.5

The discrepancies between calculated and "measured" values of r_c/r_l emphasize also the need for refinement in our theoretical description of the burning process. Thus it is apparent that the introduction of a spherical reaction shell of finite thickness will lead to lower values of T_c and also to lower effective values of r_c/r_l; as indicated in footnote 9, a similar effect is produced also if proper allowance is made for dissociation by assuming that chemical equilibrium is established at every point. Presumably the changes in T_c and in r_c/r_l will largely compensate for each other in the calculation of K' or $\dot{m}_F$, thereby accounting for the satisfactory agreement between calculated and observed values of $\dot{m}_F$.

In conclusion it seems appropriate to note that some experimental evidence exists which is not in accord with the idea that r_c/r_l is constant. Thus Hall and Diederichsen (10) state that their studies of the burning of single drops of fuel suggest that the distance between the flame front and the drop surface remains constant.

D Effect of Pressure on the Burning Process

The results of the present simplified analysis indicate that the only dependence of the burning rate on pressure occurs through the variation of the boiling points and latent heats of evaporation with pressure. The values of T_c and r_c/r_l are essentially independent of pressure. The results of Hall and Diederichsen show that the burning rate is roughly proportional to the one-fourth power of the pressure (10). Although the present analysis does not lead to this simple functional relation, detailed calculations show that the burning rates, as predicted by our theory, increase with pressure, primarily because of the decrease of latent heat of evaporation at the higher boiling temperatures associated with the increased pressure. Again it is clear that a quantitative description of the dependence of K' or $\dot{m}_F$ on pressure requires extension of the present analysis in several respects. Thus chemical reaction rates are sensitive functions of the pressure (for a

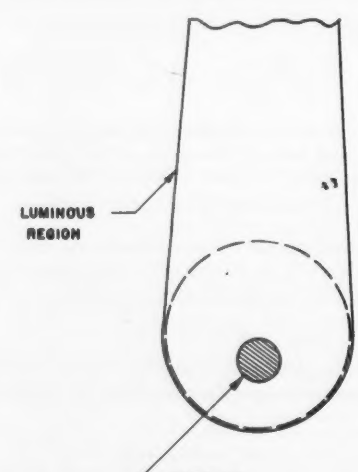

FIG. 3 SCHEMATIC DIAGRAM OF FLAME FRONT SURROUNDING A BURNING DROPLET

complicated process, an over-all dependence of the reaction rate on the square of the pressure is not unreasonable) and, therefore, a very weak dependence of $\dot{m}_F$ on reaction rates could account for the observed variation of $\dot{m}_F$ with pressure. Furthermore, the effects of radiant heat transfer to the droplet surface, which have been neglected in the present study, increase rapidly with pressure and could account for a weak dependence of $\dot{m}_F$ on pressure. Finally, the role of the inevitable convection currents requires quantitative study and may well lead to a slight variation of $\dot{m}_F$ with pressure.

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Technical Notes

Unstable Burning of Solid Propellants

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A THEORY of unstable or so-called "resonant" burning in solid-propellant rockets advanced by Cheng (1)[2] apparently was formulated in an effort to obtain analytical results in qualitative agreement with the experimental findings of Smith and Sprenger (2), who established the long-suspected fact that the irregular pressure peaks observed in tests of high-energy propellants are intimately associated with the occurrence of high-amplitude oscillations of the propellant gases in acoustical modes characteristic of the burning charge cavity. Cheng's analysis is predicted upon a mechanism for self-excitation of the oscillations which assumes that the instantaneous burning rate of the propellant (at a given initial propellant temperature) depends on pressure alone, according to the commonly encountered steady-state burning-rate law, $r = cp^n$. The experimental data, however, were obtained with propellants exhibiting so-called "plateau" burning behavior; i.e., a burning rate which increases with pressure ($n > 0$) only up to a certain point (approximately 1000 psi, for the propellants concerned), and remains constant ($n = 0$) at pressures above that level. A considerable number of the test firings summarized by Smith and Sprenger, as well as many others subsequently conducted at this Laboratory, manifested unstable burning at pressure levels high enough to assure constant-burning-rate operation, were pressure alone the governing factor. In view of this fact, it would appear that a pressure-dependent burning rate is not an essential feature of the instability phenomenon. Of course, the validity of any empirical approximation for steady-state burning is questionable when applied to a situation involving rapidly varying conditions.

Possibly as a result of the assumption mentioned above, Cheng's analysis leads to conclusions which are refuted by experience. The first is that propellant grains with cylindrical perforations (internal-burning tubes) are more unstable than grains with annular perforations (rod-in-shell charge configuration). Extensive static testing at this Laboratory, on the other hand, has indicated that the annular charge cavity is by far the more prone to "resonate." For instance, spectrum analyses of high-frequency-response pressure records obtained in repeated tests of two different motors employing multigrain charges with both cylindrical and annular flow channels invariably indicated that any observed burning irregularities were associated with oscillations in the annular passage. A second conclusion, that the tendency toward instability increases as burning of the charge progresses, is also not generally valid. Apparently on the basis of the five firing curves presented by Smith and Sprenger, Cheng states that "abnormal pressure peak is always preceded by a period of smooth operation," and he employs this induction as a test of his theory. Unfortunately, no such generalization is possible. Although it seems reasonable that charges which depend upon nonburning "resonance rods" for stabilization would become less stable as burning progresses and the influence of the rod is reduced, some high-performance motors show instability only at the start of burning. It is suggested that the latter behavior may be associated with the flow conditions at the aft end of the charge, as discussed later.

It is significant that resonant burning seems to occur only in cavities or channels where the great proportion of the surface exposed to flow is composed of burning propellant. While this behavior is partly attributable to the different boundary conditions prevailing at the burning and nonburning surfaces, as brought out in Cheng's laminar-flow analysis, the inert surfaces also are thought to contribute significantly to stability by introducing turbulent damping into the system. An agency difficult to include in theoretical treatments, "damping" at present affords the only practical means of suppressing unstable burning observed with high-energy solid propellants without lowering the propellant specific impulse. With internal-burning grains, it is conventionally introduced either by the use of inert members (rods, vanes, or baffles) and/or irregularly shaped cavities to absorb acoustical energy and/or to interfere with the ideal particle-velocity patterns characteristic of the tangential modes of oscillation and promote turbulent mixing in the flow channel. The stabilizing influence of slots or holes in the web of tubular grains, for instance, is probably attributable to dissipation of the acoustic waves by the mixing of the flow emerging from the hole or slot with that in the main channel. It may also be pertinent to recall that in the development of external-burning cruciform grains of JPN ballistite, as described by Wimpress (3), it was found necessary to arrange the inhibitor strips in a nonsymmetrical, helical pattern in order to obtain stable burning characteristics. In the cruciform section, pairs of burning surfaces are situated at right angles to one another, and the damping influence of the motor wall (conceivably attributable to acoustic absorption and/or vorticity generated by nondiminished fluid shearing action at the inert boundary) is reduced. A reasonable conjecture is that the helical inhibiting pattern provided the needed dissipative action by including a helical flow around the grain, since photographic viewing of the reaction of such grains in static tests revealed that the grains rotated in the chamber while burning. In the subsequent tests of hexaform and octaform grains, helical inhibiting patterns were also used to promote smooth combustion.

It is well known that the stability of burning in solid-propellant rockets may be influenced by the flow conditions at the aft end of the propellant grain. Smith and Sprenger investigated the influence of the aft seal upon the stability of a tubular charge, but reached no precise conclusions. Cheng advanced some analytical conclusions regarding the effect of the end seal, but his study considered no viscosity effects at the orifice, and the dimensions of the seal entered only as a boundary condition for a nonviscous acoustical problem. (Incidentally, his conclusion, that the effect of increasing the diameter of the end seal is destabilizing, is not reconciled with the smooth burning realized by Smith and Sprenger using no seal at all.) The writer subscribes to the widely held view that the flow at the aft end of the grain acts as a source of aerodynamic noise (generated by a flow instability for which viscosity is essential), which in turn excites the combustion oscillations. Development tests of an external-burning, hexaform grain conducted by the writer in 1945 showed that the firing-curve irregularities manifesting resonance became pronounced when the Mach number of the gas flow at the aft end of the grain (as determined by the ratio of nozzle throat area to charge port area) assumed values greater than about 0.5. The dependence of noise level on Mach number, as described by Kramer (4), for instance, is in qualitative agreement with

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[2] Numbers in parentheses refer to References at end of paper.

EDITOR'S NOTE: This section of JET PROPULSION is open to short manuscripts describing new developments or offering comments on papers previously published. Such manuscripts are published without editorial review, usually within two months of the date of receipt. Requirements as to style are the same as for regular contributions (see first page of this issue).

this result. Also, recent fragmentary experience at this Laboratory indicates that burning stability may be influenced by the aerodynamic design of grain-support traps; namely, that trap legs with smooth profiles may possibly tend to promote resonance more than do legs with bluff, unstreamlined cross sections. Although this observation will require further verification, it appears consistent with the propeller-noise studies of von Wittern (5), who reported that aerodynamically poor profiles generate a relatively small band of frequencies around the frequency of the von Kármán vortex street, while smooth profiles generate a broad spectrum.

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Comments on Supersonic Ramjet Diffusers

FRANK CAMPAGNA[1] and FRANK KREITH[2]

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An excellent review of some of the basic types of supersonic ramjet diffusers by F. H. Clauser appeared in the March-April 1954 issue of Jet Propulsion. However, since the original presentation of this paper in 1945, another type of ramjet diffuser has been developed which, in view of its very attractive operating characteristics, should be included in an up-to-date survey. This diffuser is essentially a reversed De Laval nozzle whose converging section is perforated in order to avoid the internal contraction ratio limitation and the hysteresis of the Kantrowitz type of diffuser illustrated in Figs. 3, 4, and 5 of Clauser's article.

In a perforated diffuser the detached shock wave can be caused to move toward the diffuser inlet by opening the perforations and thus reducing the external spillage. By a further increase in the perforation area the shock wave can be "swallowed" (e.g., brought inside of the diffuser) and caused to move near the diffuser throat. In this manner the supersonic flow can be slowed down to Mach numbers near unity before the shock occurs, thereby effecting nearly isentropic recovery. Furthermore, the perforations act as automatic shock position stabilizers since small disturbances cannot move the shock wave outside of the diffuser once it has been stabilized there. The reason for this is that in the supersonic portion of the diffuser (upstream of the shock) the pressure existing locally will be only slightly greater than the external free-stream pressure and therefore only a small amount of spillage through the perforation will occur. On the other hand, in the subsonic portion of the diffuser (downstream of the shock), the local pressure will be considerably greater than the pressure of the free-stream and thus considerable spillage will occur in this region. If a disturbance causes the shock to move away from the diffuser throat, more of the perforation area will be exposed to subsonic spillage and the shock will return to its stable position.

J. C. Evvard and J. W. Blakey[3] have demonstrated that such a diffuser will operate successfully at a flight Mach number of 1.85, but there appear to be no data available regarding the performance of a perforated diffuser at higher Mach numbers.

An investigation of perforated diffusers at Mach numbers up to 4 has been conducted at Lehigh University by means of a hydraulic analogy.[4] This investigation showed that the detached shock wave can be swallowed, decelerated to lower Mach numbers, and stabilized near the throat at flight Mach numbers up to 4 by adjusting the perforation area. Figs. 1, 2, and 3 are pictures taken of a two-dimensional analog to a perforated diffuser at various openings of the perforations. These pictures illustrate the process of swallowing the shock as the perforations are opened. Close agreement between the experimental results and normal shock theory was obtained. The results of the study indicate that a perforated diffuser can be used effectively at higher Mach numbers (at least up to 4) to achieve near isentropic pressure recovery, reduce the additive drag and external spillage, and also provide an automatic stabilization of the shock within the diffuser.

It is suggested that this type of diffuser offers attractive features and thus merits consideration along with those types of diffusers presented by Professor Clauser in the original article.

[1] Formerly mechanical-engineering student, Purdue University; now with The Glenn L. Martin Co., Baltimore, Md.

[2] Assistant Professor, Department of Mechanical Engineering. Mem. ARS.

[3] "The Use of Perforated Inlets for Efficient Supersonic Diffusion," NACA RM E51B10, April 1951.

[4] The results have been presented at the ASME Lehigh Valley section meeting, April 23, 1954, in Easton, Pa.

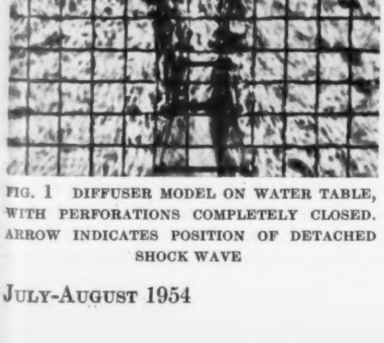

FIG. 1 DIFFUSER MODEL ON WATER TABLE, WITH PERFORATIONS COMPLETELY CLOSED. ARROW INDICATES POSITION OF DETACHED SHOCK WAVE

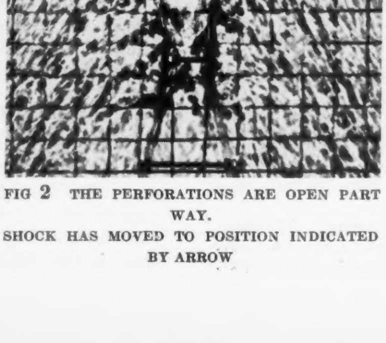

FIG 2 THE PERFORATIONS ARE OPEN PART WAY. SHOCK HAS MOVED TO POSITION INDICATED BY ARROW

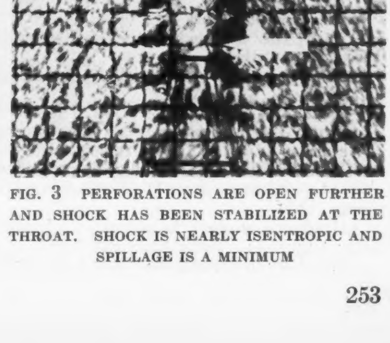

FIG. 3 PERFORATIONS ARE OPEN FURTHER AND SHOCK HAS BEEN STABILIZED AT THE THROAT. SHOCK IS NEARLY ISENTROPIC AND SPILLAGE IS A MINIMUM

The Physical Structure of Turbulent Flames[1]

MARTIN SUMMERFIELD,[2] SYDNEY H. REITER,[3] VICTOR KEBELY,[4] AND RICHARD W. MASCOLO[5]

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Turbulent flames of the type that occur in ramjet combustors were examined experimentally under idealized conditions: homogeneous mixture of fuel gas (methane) and air; uniform velocity profile of the stream; controlled turbulence intensity; and simple pilot flame-holders instead of complex bluff-body flame-holders. Measurements were made of spectral emission distributions of reaction intermediates (OH and CH) and reaction products (H_2O) across the flame zone; of the fluctuations of flame conductivity; of temperature distributions across the flame zone; and of the apparent sizes of the inhomogeneities of the flame zone. The results indicate that the widely accepted theory that a turbulent flame is simply a wrinkled laminar flame, or a group of laminar flamelets, cannot be correct. The only model consistent with these observations is that a turbulent flame is a zone of distributed reaction, similar to a laminar flame except that the reaction rate laws and transport processes are modified by the presence of turbulence. A theory of turbulent flame propagation based on this concept seems to agree with the measured flame speeds.

Introduction

THE study of turbulent flames is of considerable importance in connection with the development of high-speed, high-output ramjet-type combustors. It is known in a practical way that intense turbulence in the approach flow produces compact flames with effectively high propagation velocities. In order to relate the propagation velocity and the combustion intensity to the nature of the approach turbulence by a quantitative theory, the physical structure and the basic mechanism of a turbulent flame must first be understood.

In recent years there have been a number of attempts at a theory of turbulent flame propagation, all of them resting on the notion that a turbulent flame is really a laminar flame greatly distorted and wrinkled by the turbulent flow, dancing about irregularly in the zone described as the flame brush, and propagating at high velocity by virtue of the increase in the area of the laminar flame sheet due to wrinkling. The various investigators, Damkohler (1)[6], Schelkin (2), Karlovitz (3), and Scurlock (4), who have approached the problem in this way, differ mainly in the statistical analysis of the dancing laminar flame. There is very little experimental evidence in direct support of this physical model, and the present authors seriously question the interpretations that have been made of even these few experiments. An important objection raised by Longwell (5) cannot be dismissed: In certain ramjet-type burners, the volumetric intensity of combustion is so high that the turbulent flame brush could not possibly contain enough laminar flame sheets to provide the laminar flame area needed to account for the observed combustion intensity.

About 18 months ago the senior author of this paper proposed an alternate physical model for the turbulent flame zone, namely, that it is a region of distributed reaction, with smooth spatial variations of the time-average values of composition and temperature somewhat like a thickened laminar flame. It was believed that this model would apply particularly to flames with high intensity turbulence. According to this model, the reaction zone would be characterized by special reaction rate functions (depending on the turbulence) which would govern the transition from unburned fuel and air on the cold side, through the region of short-life intermediates and partial combustion, to the region of stable products on the hot side. On the basis of a model such as this, it is possible to derive an expression for turbulent flame speed. Similar ideas along this line have been expressed by von Kármán and Marble (6).

Experiments Concerning Flame Structure

A series of experiments was planned to test the validity of this distributed reaction model as opposed to the distorted laminar flame model currently identified mainly with the theory of Karlovitz. A steady-flow burner with a rectangular 2-in. $\times$ $^1/_2$-in. port was used to burn a premixed stream of methane and air issuing into the open atmosphere. Flow speeds ranged from 30 to 100 ft/sec; mixtures ranged from 70 per cent stoichiometric (lean) to 90 per cent; turbulence intensities up to 10 per cent were produced by grids. The flame was anchored by two narrow hydrogen flames burning along the 2-in. sides. The flame brush appeared effectively two-dimensional.

In this short note only a brief statement concerning each test can be given. A more complete paper will be published at a later date.

1 Spatial Distribution of Characteristic Radiations

If the flame brush consists indeed of a fluctuating laminar flame or segments of laminar flames, then all of the characteristic radiations normally emitted by a steady laminar flame should be observable in a long exposure over the entire area of the flame brush, with allowance for a possible spatial displacement along the stream lines of less than 1 mm between the onset of emission of short-life intermediates and the onset of emission of stable products, this separation corresponding to the thickness of the reaction zone of a laminar flame (7). In these experiments, particular attention was given to 4300 AU radiation due to CH and 9250 AU radiation due to H_2O (8). Traverses were made through the flame brush by two methods: (1) The image of the flame was focused on the slit of a Hilger intermediate quartz spectrograph so as to provide a cross-cut sample of the radiation emitted by the flame. The photographic densities along the 4300 AU band and along the 9250 AU band were compared: it was found that CH radiation appeared strongly 3 mm or more inside the H_2O radiation. (2) The flame was photographed with a camera through a 4300 AU interference-type filter and also through a similar 9250 AU filter, and the two images were compared. The findings of the preceding spectrographic experiments were confirmed. These results appear to be inconsistent with the wrinkled laminar flame model.

2 Fluctuations of Electrical Conductivity

Karlovitz has reported experiments made by inserting into the turbulent flame zone a bare wire probe connected to a d-c amplifier circuit, the output of which was observed on a pulse counter (9). It was reported that the output signal fluctuations behaved as though a laminar flame was oscillating in space in the vicinity of the probe and that at times the probe

[1] This paper is based on the Master of Science theses of the three junior authors.

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[6] Numbers in parentheses refer to References at end of paper.

was wholly out of the flame sheet and at other times it pierced the flame sheet, as indicated by a series of pulses that were uniform in magnitude but statistically random in duration. Our experiments with similar equipment employing an output oscilloscope instead of a pulse counter did not produce signal fluctuations of this kind at all; the scope deflections were random in magnitude as well as random in duration; the flame resistance oscillated with values in the range of a number of megohms; the average interval between successive peaks was about 10^{-4} sec. Comparison was made with the signal given by a pure laminar flame, with the result that the only possible interpretation is that the turbulent flame is a zone of distributed reaction containing randomly distributed pockets of ionization of widely varying concentrations. The observations cannot be reconciled with the wrinkled laminar flame model.

3 *Temperature Distribution*

If the flame brush is really a dancing laminar flame which spends 50 per cent of the time on one side of its most probable position and 50 per cent on the other side, then the temperature profile along a stream line as indicated by a thermocouple should show 50 per cent of the adiabatic temperature rise at the most probable position. The most probable position, according to this model, would be the place where the radiation emission due to intermediates such as CH is most intense. Traverses were made through the turbulent flame to test this idea, using chromel-alumel thermocouples made by spot-welding the two wires together (10). The location of the most intense CH radiation was determined by analyzing 4300 AU filtered photographs with a microdensitometer. It was found in several such tests, made under various conditions, that the point of most intense radiation was considerably on the hot side of the midpoint of the temperature traverse, perhaps at 70 per cent or more of the temperature rise. (These data are still being analyzed, so that this figure is still rough.) This result is inconsistent with a wrinkled laminar flame model, but it clearly suggests a distributed reaction zone with light emission being strongest at the hot side of the flame.

4 *Apparent Sizes of Local Inhomogeneities*

In most of the tests the effective turbulent flame velocity was less than 6 times the normal burning velocity of the laminar flame. According to the wrinkled flame model, the area increases due to turbulent motion should be no more than 6-fold. If this model is correct, a short-duration (20 microsec) spark shadowgraph should be able to resolve the wrinkled flame surface fairly well because of the relatively moderate degree of distortion. The pictures that we have taken indicate instead a highly granular flame zone, with many irregularities as small as 1 mm and possibly even smaller. Notwithstanding the difficulty of differentiating between composition inhomogeneities and temperature inhomogeneities, and despite the granulation that must occur by superposition of many irregularities within the flame along the line of sight, it is unlikely that these pictures represent merely a moderately wrinkled laminar flame or that flame fronts can be detected positively at all. It is equally possible that the irregularities visible in the pictures are the result simply of the statistical fluctuations of temperature and composition.

Flame Speed Correlation

A theory of turbulent flame propagation developed by the senior author makes use of the distributed reaction zone model by treating the turbulent flame with the well-known thermal flame equation with appropriate terms for the local reaction rate and the thermal diffusivity under turbulent conditions. (Details are reported in the M.S.E. Thesis of S. H. Reiter.) The principal result of this theory is the equation

$$\frac{S_T d_T}{\epsilon} = \frac{S_L d_L}{\nu} = \text{function only of } (f/a) \text{ ratio}$$

S is the flame speed, d is the effective depth of the reaction zone, ϵ is the turbulent diffusivity for momentum, ν is the molecular kinematic viscosity, and subscripts T and L refer to turbulent and laminar, respectively.

The eddy diffusivity in the preceding equation is the value on the cold side of the flame; similarly, the cold value of the kinematic viscosity is used. In the absence of experimental data on the eddy diffusivity variation in the flame zone, the simple assumption was made that it depends on temperature according to a law similar to that for ν. The value of ϵ in the approach flow was estimated from published correlations of turbulence behind grids (12), and turbulence intensities were determined from the cross stream diffusion of helium introduced as a tracer and measured by a thermal conductivity bridge (13). Flame speed was determined by dividing the flow rate by the area of the flame along the maximum intensity contour. Flame depth was estimated from the thickness of the brush at a definite position on each flame photograph; another method of measuring flame thickness is being tried, the volume of the flame divided by its area.

Measurements of flame speed and flame depth made at various flow speeds and turbulence levels, for a range of mixture ratios, seem to be correlated fairly well by this equation. At about the stoichiometric fuel-air ratio, the value of $S_T d_T/\epsilon$ is approximately 10. On the basis of laminar flame thickness measurements reported by Dixon-Lewis (11), about the same value is calculated for $S_L d_L/\nu$. Additional data are now being analyzed and will be reported completely at a later date.

In conclusion, it seems necessary in the face of this evidence to abandon the fluctuating laminar flame description of turbulent flames in favor of a distributed reaction zone model.

Acknowledgment

The authors are grateful to the Guggenheim Jet Propulsion Center of Princeton University for an allocation of $3000 in support of this research.

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Jet Propulsion News

Alfred J. Zaehringer, American Rocket Company, *Associate Editor*

Rockets and Guided Missiles

THE Corporal is a surface-to-surface long-range ballistic missile now being manufactured by the Firestone Tire and Rubber Company for Army Ordnance. According to a recent release by the Defense Department, the Corporal descended from the Corporal E series of rockets developed by the Jet Propulsion Laboratory at the California Institute of Technology. The missile is handled by means of a vehicle which not only serves to transport the rocket but also serves as a servicing and launching platform. The missile is fired in a vertical position and is capable of delivering an atomic warhead to ranges beyond conventional artillery. No details of the propulsion system or dimensions were given.

Another Army Ordnance rocket revealed was the Honest John, a long-range bombardment rocket, about 15 ft long and 30 in. in diam. Weighing several tons, the weapon was developed by Douglas Aircraft Company. First firings were made at White Sands in 1951 and large-scale production began in 1953. The unguided rocket is fired from a self-propelled launcher and is aimed and fired, using conventional artillery practices. Atomic or conventional high explosives can be carried in the warhead.

PRESS reports reveal that Aerojet-General Corporation has developed a solid propellant RATO booster of 18,000-lb thrust for the Air Force. Duration is for 2.5 seconds. In addition, Aerojet has reported solid propellant boosters of up to 33,000-lb thrust.

THE application of atomic energy for rocket propulsion will represent difficult engineering tasks, it was asserted by a General Electric Company scientist at the Knolls Atomic Power Laboratory. Although an atomic reactor produces a source of high temperature useful in a rocket engine, temperatures already available with chemical fuels are somewhat beyond the abilities of present-day metals to withstand. The power-to-power plant weight ratio for conceivable reactors for jet propulsion would, at present, be somewhere in the vicinity of ten and a hundred times poorer than with a chemical-fueled rocket engine.

VERONIQUE is a new high-altitude French research rocket. Designed for an altitude of 400,000-ft, it is propelled by a rocket engine developing 8800 lb thrust for 35 sec. Propellants are nitric acid and gasoline. Chamber pressure is about 285 psi and exhaust velocity is 6600 fps. The rocket is 19.7 ft long and 21.6 in. diameter. Weight is 2200 lb. Burnout velocity is reported to be 3100 mph. The rocket is stabilized during launching by four cables attached to the missile and to ground drums on the launching platform. Two of the cables are longer than the other two, thus giving the rocket the correct "tilt." When the missile is at the proper angle, explosive bolts sever the cable connections. Successful flight tests have been reported by the Vernon aeronautical and ballistic research laboratories developers.

ALTHOUGH security still remains rather tight concerning the Sperry Sparrow air-to-air missile, some details have been divulged. The Navy missile has been produced by Douglas Aircraft and Raytheon Manufacturing Company, but recent work rests with Sperry Gyroscope. The 300-lb missile employs a solid propellant. Range is about 5 miles and speed is about Mach 3.

OVER 1100 rockets and guided missiles have been launched from the Australian Woomera Proving Ground since 1950. Press reports say that 700 rockets and 440 missiles have been fired from the site. Included in these totals would be the new British air-to-air and air-to-surface missiles recently announced, the Fairey vertical-take-off rocket-propelled test vehicles (Beta I), and the newly announced Ladybird and Scarab rockets. The Ladybird, with an impulse of about 10,000 lb-sec and a motor operating time of about 6 sec has a total weight of about 100 lb. The Scarab also operates for about 6 sec, but the 175 lb rocket uses an impulse of about 20,000 lb-sec. Both rockets employ a cordite-type solid propellant.

THE Snarler, a 2000-lb thrust lox-alcohol engine has been produced by Armstrong-Siddeley. Used as a RATO unit on the Hawker fighter, the Snarler weighs about 215 lb empty. Propellants are fed by pumps driven by the main aircraft engine.

HIGH-POWER rocket engines were forecast by North American Aviation when it revealed that it had built and tested rocket engines with a jet horsepower rating much greater than that being delivered by Hoover Dam. The Hoover Dam is capable of generating about 1.7 million hp.

Aircraft

SOME information has been released about the new Republic fighter, the F-103. The configuration of the craft is said to consist of an extremely long fuselage and small delta wings. Weight of the craft will be low, considering size, with extensive usage of titanium expected. Meanwhile Republic stated that it is moving its top-secret F-105 fighter project from its New York engineering offices to its main plant at Farmingdale, N.Y. The F-105—latest development in the USAF "century" series of fighters—is the highest number yet assigned to a fighter type.

A NEW prototype jet trainer is currently being demonstrated by the Lockheed Aircraft Corp. The 600-mph plane is powered by an Allison J33-A-16A turbojet engine and retains many features of the present T-33 jet trainer now being used by the Air Force. New features include better visibility for both student and instructor, increased engine thrust, a deceleration drag chute, anti-stalling wing slots, anti-spin stabilizer, and automatic seat ejection. Approximate dimensions of the new plane are: length, 38 ft; height, 13 ft; span (including 230-gal tip tanks), 42 ft.

Lockheed Aircraft

New Lockheed jet trainer

EDITOR'S NOTE: The information reported in this Section has been selected from approved news releases originating with the Department of Defense, private manufacturers, universities, etc., and from published news accounts in journals and newspapers. The reports are considered generally reliable, although no attempt has been made to verify them in detail.

THE Japanese firm, Kawasaki, has signed a contract with Lockheed Aircraft to build F-94C Starfire jet interceptors and T-33 jet trainers for training and defense purposes.

THE Boeing jet transport, the 707 (below) is scheduled to fly this summer, according to the Seattle, Wash., company. Built at a cost of about $20 million, the craft could carry 80–130 passengers at a cruise speed of 550 mph. Expected production cost of the 707, which is powered by four P&W J-57 turbojet engines, is placed at $4 million. Weighing 190,000 lb fully loaded, the 128-ft long plane features swept-wings (span 130 ft) with engines mounted in outboard pods. The 707 is being built as a prototype model for demonstration to the military services and commercial airlines.

Boeing Airplane

Boeing 707 Jet Transport

BOEING B-47E Statojet bombers now being delivered to the USAF have added power for take-off. An alcohol-water injection system is used with the turbojets to increase power, and 33 externally mounted RATO bottles provide 33,000 lb

General Electric

B–47 uses injector take-off

Boeing Airplane

B–47 external rocket power

of thrust. The newer production models have a maximum gross weight of about 200,000 lb, more than 15,000 lb more than earlier models.

ACCORDING to Shell Oil scientists, considerations are being given to circulate jet fuels used in supersonic aircraft around the plane. Air compression produces 200 to 580 F temperatures. Therefore investigators are seeking to circulate fuel as a coolant around the plane. Such critical parts as electronic equipment, hydraulic systems, engine lubricants, and skin need cooling. One problem now being encountered is that stable fuels (such as JP-4), when heated to 300 F even

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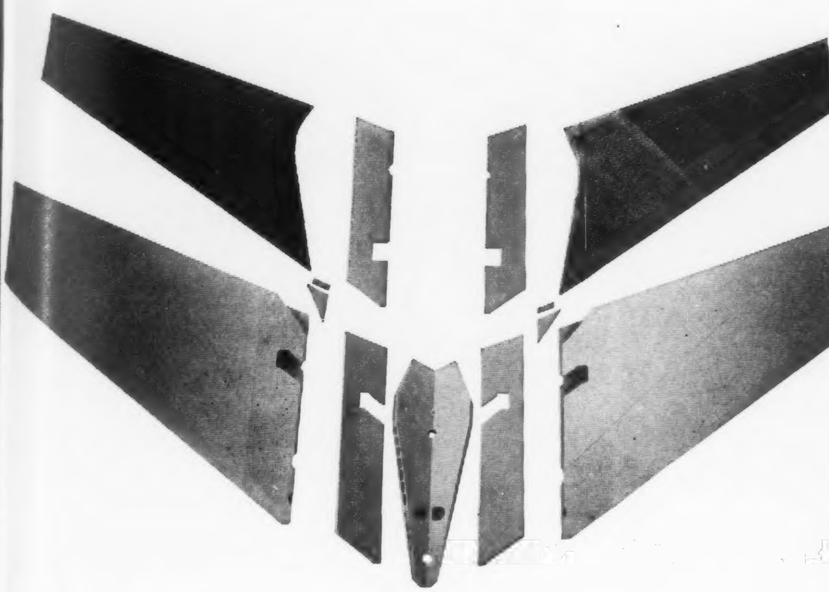

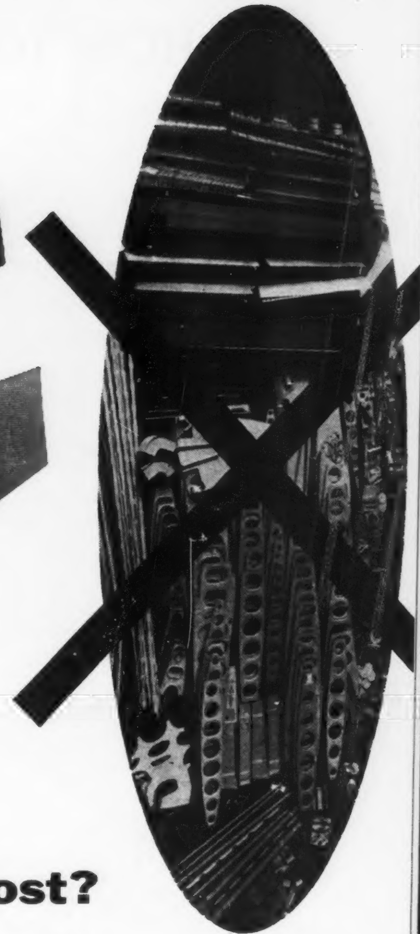

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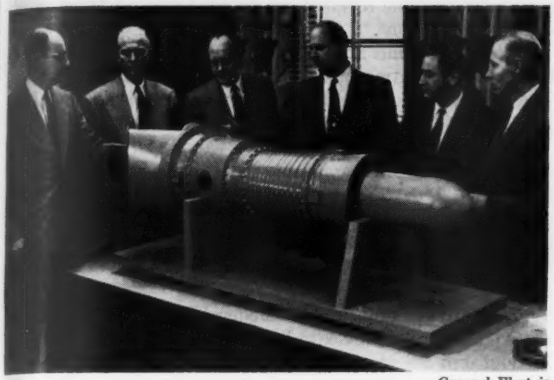

General Electric

XT-58 lightweight turbojet

for such short periods as 3 seconds, tend to form insoluble deposits which clog filters, screens, and nozzles. Conventional gasoline inhibitors presently available are reported to to be only mildly effective or deleterious.

Turbojets

AIR SECRETARY Harold Talbott disclosed that the USAF is developing turbojet engines of about 25,000-lb thrust.

THE General Electric Company announced that it is developing a lightweight gas-turbine engine (above), the XT-58, to power Navy helicopters. The only details released were that it was comparable in size to a conventional automobile engine but with 6 to 8 times the power.

TEST stand runs have been made on the new P&W J-57 turbojet engine. Featuring a split compressor, the J-57 is designed to deliver about 15,000-lb thrust (21,000-lb thrust with afterburner). The engine costs about $250,000.

THE GE J-73 turbojet design is aimed at producing 15,000-lb thrust and features low frontal area. Employed is a single-spool compressor with stators of variable pitch.

New Applications for Rockets

A MINIATURE rocket motor, with a 0.005-in.-diam nozzle, is used to propel liquids at a speed of Mach 1.75 in a new supersonic hypodermic. Developed at UCLA, the liquid is propelled by the detonation of a small wafer of nitrosoguanidine and is used for direct injections to such human targets as internal organs and tumors.

EXPERIMENT, Inc., of Richmond, Va., has reported that its patents dealing with the synthesis in a ramjet-type reactor of ethylene and acetylene from hydrocarbon fuels have been assigned to the Chemical Construction Company. Intensive industrial development is said to be under way.

POWER packs, employing a solid propellant charge, are being studied for use in starting and stopping components of heavy machinery such as turbines and motors. Solid propellants already are being used as turbine starters for turbojet aircraft.

THE Southwest Research Institute is developing a rocket motor, of high thrust for short duration, for applications in oil wells. A solid propellant charge is used.

MANY jet processes such as the thermal fixation of nitrogen and the formation of carbon black are being studied by industry.

Facilities

PHILLIPS Petroleum Company reports that it has made large-scale firings of ATO units using solid fuels produced from petroleum raw materials. The company operates the big Air Force Plant No. 66 at McGregor, Texas.

AMERICAN Helicopter, Inc., is expanding its pulsejet-engine-testing facilities at its Falcon Field, Arizona, plant.

LOCKHEED Aircraft Corporation is locating its $1.0 million Missile Systems Division at Van Nuys, Calif., to deal with the design, development, and manufacture of pilotless-guided-missile systems. A staff of nearly 1000 is expected in the months ahead.

A SOLAR furnace is being used by the Convair San Diego division to conduct research with heat-resisting alloys and ceramics which may be considered for use on hypersonic missiles. Under ideal conditions, the furnace is claimed to generate temperatures of up to 8500 F. A polished aluminum reflector, 120 in. in diam, focuses the sun's rays to a $^5/_{16}$-in. diam point 34 inches away.

Reverse Thrust Devices

THERE has been much recent interest in reverse thrust devices for use on turbojet aircraft. Several new announcements indicate vigorous development.

One of the first jet thrust reversers was reported by the French firm, Snecma. Reverse thrust is about half the normal positive thrust of the engine. The system uses a series of annular rings placed concentrically along the thrust line at the tailpipe. A compressor bleed is piped into the exhaust flow where the exhaust gases are deflected outward through the rings. Some losses in positive thrust, however, have been reported. The Aerojet-General Corporation, Azusa, Calif., has recently arranged to build the device under a license with Snecma.

Boeing Airplane Company recently revealed its work in this field. Of the types studied by Boeing, it was revealed that a simple clamshell over the exhaust was capable of about 45% reversal. The clamshell, an extendable device, is stowed around the exterior of the tail cone when not in use and it is extended into the exhaust flow only for operation. It is claimed that the reverser can be used in most types of jet engine installations.

Fairchild Engine and Airplane Company is reported to have a design contract with the Air Force for a thrust reverser. The unit resembles the Boeing design and consists of a pair of jawlike air scoops extending into the jet exhaust.

Marquardt Aircraft Company of Van Nuys, Calif., entered the field recently with a variable area exhaust nozzle, weighing less than 100 lb, which can provide up to 35% reverse thrust on nonafterburning turbojet engines. The device, said to have been tested, would enable the pilot to make a landing with nearly full engine power and to switch instantly to full forward thrust in an emergency.

Prof. J. Ackeret of the Swiss Federal Institute recently presented details of his device in Washington before the IAS. The Ackeret unit is a mechanical vane mounted in tail cone or afterburner. No detrimental effects on normal thrust claimed.

Two other groups are reported to be at work on reversers. The Air Force at Wright Air Development Center is said to be developing its own original design. The Engineering Division of the American Machine and Foundry Company is also doing development work.

Symposium on Pulsatory and Vibrational Phenomena

THE field of pulsation and vibration will be discussed at the 21st Annual Christmas Symposium of the Industrial and Engineering Chemistry Division of the American Chemical Society. Papers expected to be presented will deal with shock phenomena, pulse extraction, generation and effects, vibration in combustion, vibration on structures and materials, HF heating, etc. The Symposium will be held on January 7 and 8, 1955. Interested persons should contact the program chairman, DeWitt O. Myatt, Atlantic Research Corp., 901 N. Columbus Street, Alexandria, Va.

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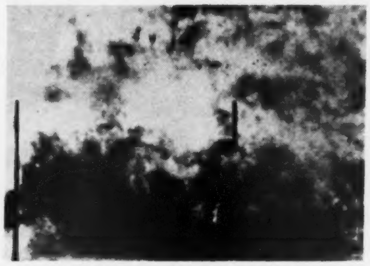
ARS News

One of many tests conducted at White Sands Proving Ground, which will be visited during Fall meeting, was Operation Push-over which called for...



...intentional toppling of fully fueled V-2. These stills, taken from film made by Cmdr. F. W. Maxwell, Jr., USN, got first public showing before New York Section

"Missile Testing, Flight, and Instrumentation" at September Meeting in El Paso-White Sands

THE New Mexico-West Texas Section will serve as hosts to the national membership on September 22–24, when 13 papers on "Missile Testing, Flight, and Instrumentation" will be presented at technical sessions in El Paso, and an organized inspection of areas of the White Sands Proving Ground will be arranged.

The papers scheduled for the sessions are listed below. The sessions will be held at the Hilton Hotel in El Paso on the first two days of the meeting. All papers will be unclassified.

On the third day transportation will be provided to WSPG for inspection tours, the details of which have not, at this writing, been completed.

Complete information and reservation forms will be sent to all ARS members as soon as final arrangements have been completed. However, those who wish to make reservations now can do so through Frank L. Koen, Jr., President, NM-WT Section, Box 381, Mesilla Park, N. M. Since some members have expressed interest in combining a trip to this meeting with their vacations, the national office will make an effort to enclose brochures describing the tourist attractions in the area—which include Carlsbad Caverns; Juarez and Chihuahua, Mexico; old Spanish missions; and many other sights. The papers are:

General Considerations in Missile Evaluation, R. Weller, U. S. Naval Air Missile Test Center, Point Mugu, Calif.

System Simulations for Missile Evaluation, John H. McLeod, Jr., U. S. Naval Air Missile Test Center, Point Mugu, Calif.

Free Flight Determination in Missile Environment Generated by Solid Propellant Motors, H. Gumbel, U. S. Naval Air Missile Test Center, Point Mugu, Calif.

The Role of Environmental Testing in a Missile Program, R. A. Harmon, U. S. Naval Air Missile Test Center, Point Mugu, Calif.

Reliability in Guided Missiles, R. P. Haviland, General Electric Company, Key West, Fla.

Generation of High Gas Pressure Through Hydraulics, Julius Kendall, Greer Hydraulics, Brooklyn, N. Y.

The Need of Fundamental Knowledge in Shock and Vibration of Missiles, G. A. Garcia, U. S. Naval Air Missile Test Center, Point Mugu, Calif.

Instrumentation Radar for Missile Testing Ranges, S. B. Adler and L. T. Carapelletti, Radio Corporation of America, Moorestown, N. J.

Which Way is Up? (Verticality measurement), David Balber, Kearfott Company, Clifton, N. J.

Radar and Guided Missiles, W. Hiltz, White Sands Proving Ground.

Effects of Environment on Guidance, Author un-named, White Sands Proving Ground.

Effects of Sub-gravity on Animal Performance, Major D. G. Simons, Holloman Air Development Center, Holloman Air Force Base, Tex.

Some New Approaches to Missile Guidance, Paul H. Savet, Arma Corporation, Garden City, N. Y.

New ARS Awards Announced

Committee Invites Recommendations for Candidates

THE Awards Committee wishes to invite recommendations for recipients of the various ARS awards. This year, in addition to the existing four awards, there will be two new ones.

The first new award is a "general purpose" award to be given for outstanding accomplishments in fields related to rocketry and jet propulsion. In this flexible manner, the Society hopes to recognize outstanding achievements in any related endeavor, such as ramjets, high-altitude research, field tests, guidance, or instrumentation development.

The second award is for outstanding accomplishment in astronautics, an interest which was instrumental in the formation of the Society.

In the near future these two new awards will be given suitable names after outstanding pioneers in the field.

Recommendations and suggested nominations for these and the following awards should be submitted to the chairman of the committee: G. P. Sutton, 9540 Rives Avenue, Downey, Calif. With each name submitted there should be an explanation of the reasons for selecting the specific candidate, and recommendations must be received by the Awards Committee on or before August 19, 1954.

Robert H. Goddard Award

For outstanding contribution to the development of rocket propulsion in the liquid-propellant field. (John Shesta, Reaction Motors, Inc., 1948; Adm. C. M. Bolster, U.S.N., 1949; Lovell Lawrence, Jr., Reaction Motors, Inc., 1950; Cmdr. R. C. Truax, U.S.N., 1951; Dr. R. W. Porter, General Electric Company, 1952; David A. Young, Aerojet-General Corp., 1953.)

C. N. Hickman Award

For outstanding contribution to the development of rocket propulsion in the solid-propellant field. (Dr. Frank Malina, UNESCO, 1948; Dr. James A. Van Allen, Applied Physics Lab., Johns Hopkins University, 1949; Col. Leslie Skinner, U.S.A.F., 1950; Dr. William Avery, Applied Physics Lab., Johns Hopkins University, 1951; Dr. A. L. Antonio, Aerojet-General Corp., 1952; C. E. Bartley, Grand Central Aircraft, 1953.)

G. Edward Pendray Award

For major contribution to the technical literature on rocket and jet propulsion. (G. P. Sutton, North American Aviation, Inc., 1951; Dr. M. J. Zucrow, Purdue University, 1952; Dr. H. S. Tsien, California Institute of Technology, 1953.)

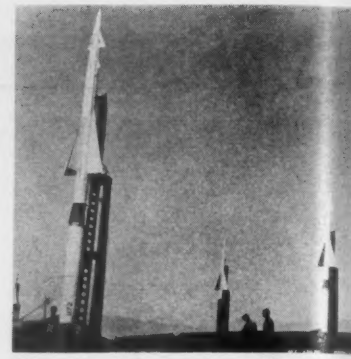
ARS Student Award

For the best paper by student members submitted during the year in the student awards competition in the general field of rocket and jet propulsion.

So much good work is being done under the various degrees of secrecy that no committee of five men could possibly know all the candidates. Each suggestion will be given the most serious attention by the Awards Committee.

The Awards Committee this year is composed of R. C. Truax, Roy Healy, Raymond Young, and J. B. Cowen, under the chairmanship of G. P. Sutton.

Technicians at Bell Labs set up simulated firing course for Nike



Nike launching section with missiles raised to firing position

Night firing of rocket engine at North American's facility in Santa Susana mountains near Los Angeles

Bell Labs and North American New Corporate Members

BELL Telephone Laboratories, New York, developer of the Nike antiaircraft missile system, and North American Aviation, Inc., Downey, Calif., active in virtually every aspect of the rocket, missile, and aircraft fields, are now ARS Corporate Members.

Included in the Corporate Membership for Bell Labs are W. C. Tinus, Vice-President, J. M. West, W. H. C. Higgins, R. R. Hough, and H. W. Bode, all from the Whippany, N. J., laboratory of the organization.

Bell undertook a study in 1945 for the Army Ordnance Corps which resulted in the authorization of a development contract for the Nike. Douglas Aircraft, also an ARS Corporate Member, developed the design of the missile and launching equipment, while Bell handled the guidance. Nike batteries are now being constructed in a reported 40 areas in the United States.

North American's Corporate Membership includes J. G. Beerer, Director of the Aerophysics Department; S. K. Hoffman, Manager of the Rocket Engine Facility and past president of the *Southern California* Section; J. A. Broadston, Propulsion Test Manager, Aerophysics Field Laboratory; T. F. Dixon, Engineering Director of the Rocket Engine Facility; and Paul R. Vogt, Group Leader of the Propulsion Design Group.

In addition to its widespread missile and aircraft work, North American has done considerable development and production of rocket engines, including the 50,000-lb thrust engine which powers the Air Force's test sled, accelerating the sled from a dead stop to 1500 mph in $4^1/_2$ sec.

ARS at Innsbruck

OUT of 30 papers slated for presentation at the Fifth International Astronautical Federation Congress in Innsbruck, August 1–6, eight will be authored by ARS members.

Included are: A. J. Zaehringer on "Solid Propellants and Astronautics"; K. A. Ehricke on "Analysis of Orbital Systems"; D. C. Romick on "Basic Design Principles Applicable to Reaction-Propelled Space Vehicles"; E. Stuhlinger on "Possibilities of Electrical Space Ship Propulsion"; H. J. Schaeffer on "Protection of Humans from Heavy Nuclei of Cosmic Radiation in Regions Outside the Earth's Atmosphere"; H. Strughold on "Space-Equivalent Conditions Within the Earth's Atmosphere; Physiological Aspects"; F. I. Ordway on "Space Flight Activities in the USA"; and I. M. Levitt on "Geodetic Values of a Minimum Satellite Vehicle."

Section Doings

Chicago. On May 26 President Andrew G. Haley met with officers and members at Illinois Institute of Technology. Among the subjects discussed was a plan for expanding membership.

Cleveland-Akron. Prof. Paul Annear, Head of the Dept. of Astronomy at Baldwin Wallace, spoke on "The Atmosphere of the Earth and Its Planets" at the Annual Banquet on May 20. President Darrell Romick introduced the following new officers: John Sloop, President, of the Lewis Flight Propulsion Lab, NACA, and Robert J. Couts, Secretary-Treasurer, Goodyear Aircraft. James J. Harford, ARS Executive Secretary, also spoke on the activities of the national office.

Indiana. On April 27 the following new officers were elected: A. R. Graham, Pres.; R. W. Foster, Vice-Pres.; D. G. Elliott, Sec.; and J. P. M. Diamond, Treas. Faculty advisor for the Section, membership of which consists mostly of students at Purdue Univ., is Dr. B. A. Reese, and the new Directors are J. M. Botje, out-going President; D.E. Robison, and D. P. Spahr.

National Capital. About 150 people heard Dr. Conway Snyder of the Oak Ridge Institute of Nuclear Studies speak on "Atomic Energy and Space Travel" at the University of Maryland on May 3. Joint sponsor of the meeting was the University chapter of Sigma Pi Sigma, national physics honor society. Dr. Snyder's principal conclusion was that the working fluid appeared most promising but that its successful utilization must await the development of more efficient reactors and better materials of construction.

An informal dinner was held at the National Press Club on May 17 in honor of A. V. Cleaver of the British Interplanetary Society, a member of ARS, who is in charge of rocket research at De-Havilland Engine Co., Ltd., Stonegrove, England. President Haley spoke on the current membership drive and F. C. Durant, president of IAF, talked about that organization.

New Mexico-West Texas. Col. John Stapp, a new ARS member whose recent rocket-sled tests at Holloman Air Development Center received nation-wide attention, spoke at an April 29 meeting at New Mexico State College.

New York. "Operation Sandy" and "Operation Pushover" were discussed by Commander F. W. Maxwell, Jr., USN, of the U. S. Naval Air Rocket Test Station, Lake Denmark, N. J., at a meeting attended by 90 on May 21. Sandy, which involved the launching of a V-2 from the *USS Midway* underway, was illustrated with an excellent color film. Commander Maxwell pointed out that normal aircraft operations were resumed 65 minutes after the missile had been launched.

Pushover, a series of tests conducted at WSPG in 1948 and 1949 during which a fully fueled V-2 was deliberately toppled after preliminary stage operation had been initiated, was illustrated by Commander Maxwell's own film (p. 265). This was the first public showing of the test. The initial test, according to Maxwell, produced a spectacular detonation of far greater magnitude than had been expected. Measures were taken to reduce the severity of the explosions, however, in subsequent tests. The experience gained in Operations Sandy and Pushover have been very profitably applied to further techniques for launching large missiles from ships, such as the firing of the Viking from the *USS Norton Sound*.

ARS President Andrew G. Haley (center) appears at recent meeting of Niagara Frontier Section. Others are D. C. Schiavone, Program Chairman, John van Lonkhuyzen, Tom Zannes, Vice-President, and Willis Sprattling, President, all of Bell Aircraft

Niagara Frontier. President Haley spoke at a dinner meeting on May 19 which was attended by about 75 members and guests (above). He stated that "the preservation of the U. S. now rests completely on the effectiveness...of its rocket projects, for in another war we will simply have to be there first with the most."

A February dinner meeting, previously unreported here, presented a discussion by Bell Aircraft's Krafft Ehricke on "The Evaluation of Rocket Flight." Officers for 1954 were announced as follows: Willis Sprattling, Pres.; Tom Zannes, Vice-Pres.; Robert Gray, Corresponding Sec. and Bill Bond, Treas.; all of Bell Aircraft Corp. Two-year directors are Noah Davis, Buffalo-Electro-Chemical Co.; Hugh Coyer, Mathieson Chemical Corp.; and W. M. Smith, of Bell. One-year directors are Dave Feld, R. A. Clark, Jerry Christ, and Harry Sylvies, all of Bell.

St. Louis. President Haley attended the organizational meeting of this newly chartered Section on May 28 at the St. Louis Academy of Science. Officers are Dr. Norton B. Moore, McDonnell Aircraft Corp., Pres.; Elzey M. Roberts, Jr., Academy of Science, Vice-Pres.; Richard Shapker, Parks College, Vice-Pres.; James J. Mazzoni, McDonnell, Sec.; Edwin Dow, Parks, Treas.; and directors are John J. O'Fallon, Academy of Science; and Thomas Stark, Parks. Headquarters of the Section will be at the Academy of Science and a program of meetings will begin in the Fall.

Southern California. Dr. Arthur H. Warner, Chief Scientist at the Office of Naval Research in Pasadena, spoke on "Guided Missile Production, an Example of the Problem," at a dinner meeting on May 12 at the IAS Building in Los Angeles. Dr. Warner was former Technical Director of the Air Force Missile Test Center in Banana River, Fla.

ARS SECTION PRESIDENTS

Alabama	**George Henderson** Redstone Arsenal
Arizona	**Anthony R. Tocco** Hughes Aircraft Co.
Chicago	**Kenneth H. Jacobs** American Machine & Foundry Co.
Cleveland-Akron	**John Sloop** Lewis Flight Prop. Lab., NACA
Detroit	**Laurence M. Ball** Chrysler Corp.
Florida	**K. K. McDaniel** Boeing Airplane Co.
Indiana	**A. R. Graham** Purdue University
Maryland	**Ivan E. Tuhy** Glenn L. Martin Co.
National Capital	**J. R. Patton, Jr.** Office of Naval Research
New Mexico-West Texas	**Frank L. Koen, Jr.** White Sands Proving Ground
New York	**Michael J. Samek** American Electro-Metal Corp.
Niagara Frontier	**W. Sprattling** Bell Aircraft Corp.
Northeastern New York	**George E. Moore** General Electric Co.
Northern California	**William J. Barr** Detroit Controls Corp.
Princeton Group	**John Scott** Princeton University
Southern California	**H. S. Seifert** Calif. Inst. of Tech.

Book Reviews

C. F. Warner, Purdue University, *Associate Editor*

Organic Chemistry, Second Edition, by Ray Q. Brewster, Prentice-Hall, Inc., New York, N. Y., 1953, 855 pages. $9.35.

Reviewed by Arthur B. Ash
Wyandotte Chemicals Corporation

While your reviewer has not taught "sophomore organic" for many years, he feels that if he were to teach the subject, he would use a text such as that produced by Ray Q. Brewster. Dr. Brewster has thoroughly covered the fundamentals of organic chemistry—35 chapters, 855 pages of text. The context is lucid; paragraphs are numbered; and the formulas and equations are numerous and clarify the text extremely well. Major recent industrial developments are included and the presentation of the interesting field that is organic chemistry should induce the students (the better ones, we trust) to pursue the subject as graduate majors.

Finally, the author "tried to write a text upon the principles of organic chemistry in which the emphasis is placed upon the mechanism of reactions." In this he has succeeded extremely well. While there is considerably more material presented than the average student could absorb in one year, the book is adaptable to the selection of topics, and the better students who pursue the subject will find the text a valuable and useful reference.

Temperature Measurement in Engineering, Volume I, by H. D. Baker, E. A. Ryder, and N. H. Baker, John Wiley & Sons, Inc., 1953, 179 pp. $3.75.

Reviewed by C. R. Foster
California Institute of Technology
Jet Propulsion Laboratory

The first four chapters of this volume serve as an introduction to the two-volume series on temperature measurement; they deal with the general concept of temperature, the several different methods available for measuring temperature, and the problems involved in obtaining the desired accuracy.

The remaining nine chapters of this first volume are concerned with the measurement of temperature of bodies in the solid state and deal primarily with thermocouple technique, since this method is the most widely useful for measuring internal temperatures of solid bodies. The different types of thermocouples are described, and the optimum temperature range and conditions for each are noted. Methods of making junctions, setting up circuits, making design calculations, and installing thermocouples in various solid materials are described in detail. The wealth of detail on the installation of thermocouples makes this a valuable reference book for the technician charged with the successful accomplishment of the thermocouple mounting as well as for the engineer responsible for the solution of the over-all temperature-measuring problem. For example, chapter nine is devoted exclusively to the technique of drilling deep small-diameter holes in various solid materials—valuable information and certainly required for a successful result. Examples of many thermocouple installations, used successfully by the authors, are given with the same attention to detail.

An extensive bibliography at the end of each chapter makes the book a handy reference for other literature on temperature measurement and related subjects.

Aircraft Instrument Design, by W. H. Coulthard, Pittman Publishing Corp., New York, N. Y., 1952, 309 pp. $7.50.

Reviewed by A. L. Klein
Douglas Aircraft Company
Santa Monica, Calif.

This book covers the instruments common in England and many American instruments. By American standards the book is not properly titled as it contains little of value to an instrument designer. The book might more properly be titled, "The Principles of Aircraft Instruments."

The principles of operation of the aircraft instruments available in England are described. Most of these instruments are similar to those available in the United States but are not necessarily identical to them. The American user will, therefore, have to read this book with caution. The trade names used, though applying to apparently identical instruments made under cross-licensing agreements, are sometimes different, and the instruments themselves are not necessarily interchangeable.

The material is well organized and gives adequately the underlying principles used in the design of a wide range of aircraft devices. It would be of little use to an instruments designer, however, as no information concerning the properties of materials, manufacturing tolerances, and similar matters is given. The book is of limited use and interest to Americans, but since a comparable American book does not exist, it may find a wide market in this country.

A History of the Theories of Aether and Electricity, by Sir Edmund Whittaker, Philosophical Library, New York, N. Y., 319 pp. $8.75.

Reviewed by E. A. Frieman
Princeton University

Sir Edmund Whittaker, already noted for his exhaustive work on analytical dynamics, at the age of eighty has continued the pattern set by his earlier work in this second volume covering the whole of theoretical physics from 1900 to 1926. The first volume, dealing with the classical theories was published in 1910 and reissued in a revised edition in 1951.

The first chapter describes the growth of experimental atomic physics, thus giving the background for the mathematical theories dealt with in later chapters. The remainder of the book is devoted to special and general relativity and the "old" and "new" quantum theories. There are over 1000 references to original papers which the author presumably studied as they appeared, and this makes him the ideal person to write this book and capture the flavor of the times.

An extremely valuable aspect of the book is the presentation of the intermediate stages in the formulation of the theories presented. Striking examples are Planck's reasoning leading to his empirical law of black-body radiation nine months before the fundamental theory was published, and Poincaré's views on special relativity a year before Einstein published his historic paper.

This book should be a valuable addition to the library of all serious students of the history of science.

An Introduction to Scientific Research, by E. B. Wilson, Jr., McGraw-Hill Book Company, Inc., New York, N. Y., 1952, 375 pp. $6.

Reviewed by R. S. Wick
California Institute of Technology
Jet Propulsion Laboratory

The scope and intent of Professor Wilson's book can best be stated by presenting a few quotations from it. From the preface: "This book is an attempt to collect in one place and to explain as simply as possible a number of general principles, techniques, and guides for procedure which successful investigators in various fields of science have found helpful. The emphasis is entirely on the practical rather than the philosophical aspects." In his introduction he states further that in every section it would be correct to include the statement: "This section is designed to introduce the reader to a topic about which whole books have been written." Thus, "This book is intended to assist scientists in planning and carrying out research. The nature of selection has been to include only topics which would hlep someone decide what to do next and are of a broad nature, not too specific to a particular scientist."

The thirteen chapters are arranged in the same logical sequence as the research program itself, namely: Choice and Statement of a Problem; Searching the Literature; Scientific Method; Design of Experiments; Design of Apparatus; Execution of Experiments; Classification, Sampling, and Measurement; Analysis of Data; Errors of Measurement; Probability Randomners, and Logic; Mathe-

Editor's Note: This issue of the Book Reviews section was edited by Dr. Irvin Glassman, Associate Editor of Jet Propulsion, during Dr. C. F. Warner's absence from his regular position at Purdue University. Dr. Warner will return to active editorship in October.

matical Work; Numerical Computations; and Reporting Results of Research.

The methods introduced and discussed in the book are illustrated with practical examples. In most cases, only a formal training up to calculus is needed to follow the author. At the end of each section references are made to more detailed accounts of the subject matter.

Professor Wilson's book is a notable contribution toward making research more systematic. Although the book is interesting to read, one cannot expect much improvement in his technique merely by reading it. The material must be reread and studied, and in many cases the reader will want to refer to the publications listed in the bibliographies. The greatest contribution, as far as the experienced research worker is concerned, is the clear presentation of introductory material on statistical methods. He will also find much of interest in the more general chapters. As to the beginner, he will do well to study the entire book.

Matter Energy Mechanics, by Jakob Mandelker, Philosophical Library, New York, N. Y., 1954, 73 pp. $3.75.

Reviewed by M. D. Kruskal
Princeton University

The author tries to show that by adding to classical mechanics Einstein's law of inertia of energy, $m = E/c^2$, the results of special relativity theory may be obtained. He has several misconceptions of this theory and the singular ability to refrain from going to extreme cases just when doing so would clearly reveal an error. There is room here for only a few examples.

The claim that the nonsymmetrical addition formula for velocities (on p. 31) "conforms with the requirement for a terminal velocity c," which is supported by putting one of the component velocities equal to c, is immediately disproved by doing so with the other instead. The discussion on pp. 35–41 would imply in a particular case that the Lorentz transformation is invalid when applied to the path of a light ray with velocity in one frame of reference orthogonal to the velocity of the other frame. The criticism on p. 47 of the relativistic law of spherical light propagation for all inertial systems applies only to the incorrect statement of the law there, in which the center of the sphere in the moving system is mislocated.

Technical Literature Digest

M. H. Smith, *Associate Editor*, **and M. H. Fisher**, *Contributor*
The James Forrestal Research Center, Princeton University

Jet Propulsion Engines

The Free Piston and Turbine Compound Engine—a Cycle Analysis, by A. L. London, *Stanford Univ. Dept. Mech. Engng. Tech. Rep.* FP-3, Aug. 1953, 32 pp.

Tooth-Type Noise Suppression Devices on a Full Scale Axial-Flow Turbojet Engine, by Edmund E. Callaghan, Walton Howes, and Warren North, *NACA RM* E54B01, March 1954, 16 pp.

A Survey of Performance Reduction, With Particular Reference to Turbo Propeller Aircraft, by K. J. Lush, *Gt. Brit. ARC R.&M.* 2757, 1954. 7 pp.

General Performance Calculations for Gas Turbine Engines, by D. H. Mallinson, *Gt. Brit. ARC R.&M.* 2684, 1954, 58 pp.

Summary Report of Development of Ram Jet Propelled Rotor, *McDonnell Aircraft Corp. Rep.* 2792, Nov. 1952, 57 pp.

Basic Compressor Characteristics from Tests of a Two-Stage Axial-Flow Machine, by W. R. New, A. M. Redding, H. B. Saldin, and K. O. Fentress, *Trans. ASME*, vol. 76, April 1954, pp. 473–481.

Experimental Investigation of Propagating Stall in Axial-Flow Compressors, by T. Iura and W. D. Rannie, *Trans. ASME*, vol. 76, April 1954, pp. 463–471.

Ducted Fans Excel Turbojets and Turboprops for Transports, by W. C. Lawrence and H. E. Hoben, *SAE J.*, vol. 62, March 1954, pp. 52–58.

Meat: the Key to A-Powered Aircraft, by A. Silverstein, *Aviation Week*, vol. 60, May 24, 1954, pp. 28–30, 34.

Jet Fuel Systems Needn't Be Complicated, by R. R. Migginbotham and W. R. Petersen, *SAE J.*, vol. 62, April 1954, pp. 25–30.

Application of Dimensional Analysis to Spray Nozzle Performance Data, by M. R. Shafer and H. L. Bovey, *J. Res. Nat. Bur. Stands.*, vol 52, March 1954, pp. 144–147.

Three Basic Designs for Jet Engine Starters (Bendix Aviation Corp.), *Aviation Age*, vol. 21, March 1954, pp. 144–146.

Turbo-Wasp Dissected; More News of the J-57 Two-Spool Turbojet, *Flight*, vol. 65, May 14, 1954, pp. 619–620.

Reds' Surprise: 15,000-Lb.-Thrust Jets, by Robert Motz, *Aviation Week*, vol. 60, May 31, 1954, pp. 12–13.

The SNECMA Jet Deviator, *Aeroplane*, vol. 86, April 16, 1954, p. 466.

Boeing Reverses Thrust Without Penalty, by Joseph S. Murphy, *Amer. Aviation*, vol. 17, May 10, 1954, p. 20.

Thrust to Drag (Boeing Thrust Reversal device), *Flight*, vol. 65, April 30, 1954, pp. 540–541.

Jet Thrust Reverser Is Safe, Practical, *Aviation Week*, vol. 60, April 19, 1954, pp. 28 to 30.

Four Firms in USAF Reverse Thrust Race, by William D. Perrault, *Amer. Aviation*, vol. 17, April 12, 1954, pp. 13–14.

The Quest for Power, by W. T. Gunston, *Flight*, vol. 65, April 9, 1954, pp. 429–444.

Boeing Model 520. . .Compressor or Powerplant, by Randolph Hawthorne, *Aviation Age*, April 1954, pp. 22–23.

Aero-Engines 1954, *Flight*, vol. 65, April 9, 1954, pp. 445–468.

Investigation of Effects of Inlet-Air Velocity Distortion on Performance of Turbojet Engine, by E. William Conrad and Adam E. Sobolewski, NACA RM E50G11, July 1950. (Declassified 1953)

Performance Investigation of Can-Type Combustor; I—Instrumentation, Altitude Operational Limits and Combustion Efficiency, by Eugene V. Zettle and William P. Cook, NACA RM E8F17, June 1948. (Declassified 1953)

Carbon Deposition of 19 Fuels in an Annular Turbojet Combustor, by Jerold D. Wear and Edmund R. Jonash, NACA RAM E8K22, Nov. 1948. (Declassified 1953)

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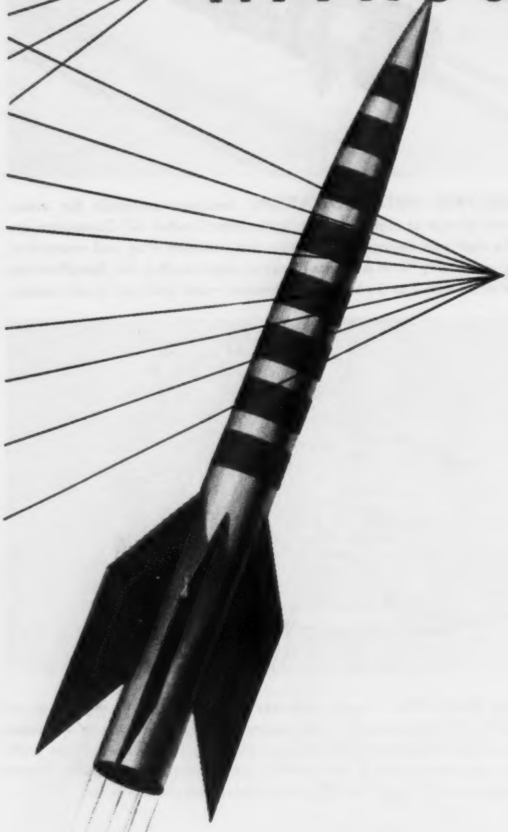

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